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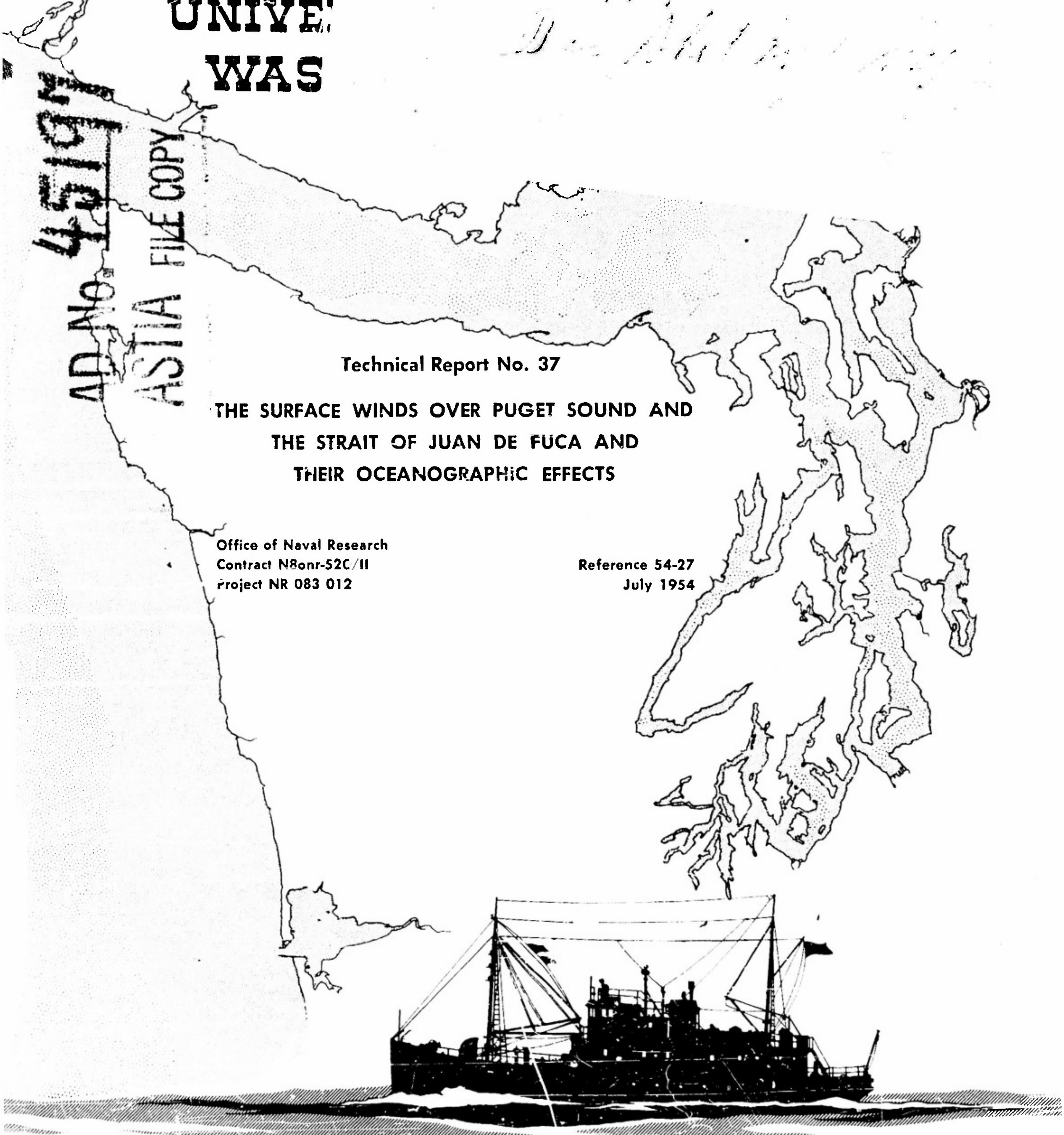

Technical Report No. 37

THE SURFACE WINDS OVER PUGET SOUND AND THE STRAIT OF JUAN DE FUCA AND THEIR OCEANOGRAPHIC EFFECTS

Office of Naval Research
Contract N8onr-520/II
Project NR 083 012

Reference 54-27
July 1954

SEATTLE 5, WASHINGTON

UNIVERSITY OF WASHINGTON DEPARTMENT OF OCEANOGRAPHY
(Formerly Oceanographic Laboratories)
Seattle, Washington

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by

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for Clifford A. Barnes
Richard H. Fleming
Executive Officer

ABSTRACT

The surface winds which occur over the waters of Puget Sound and the Strait of Juan de Fuca present a complex picture. Strongly affected by topography, they cannot be predicted or fully explained solely by consideration of the changing atmospheric pressure patterns over or near the region.

A detailed summary of accumulated surface wind reports is desirable, therefore, to satisfy the increasing demand for a reasonably accurate climatic picture of the surface flow over this region throughout the year. In particular, oceanographic and fishery investigations being conducted in these waters have shown the need for more detailed and comprehensive information of this sort than is presently available.

This report attempts to partially satisfy this need in two ways. First, all available wind report summaries have been accumulated in the form of monthly wind roses for each reporting station. Secondly, a determination has been made of the frequency and maximum duration of surface winds of above average velocity at selected stations over a three year period.

Particular meteorological situations have been selected and discussed, to serve as examples of the general or unusual flow patterns derived from the summarized data.

Some of the oceanographic effects of these surface winds are discussed, and approximate calculations are made of the maximum

heights of wind waves which may have occurred on Sound waters during the three year period for which high surface wind data were compiled. With the use of empirical formulae, semi-quantitative estimations have also been made of the stress on the water surface due to the surface wind flow, and of the currents and water level slopes which might result.

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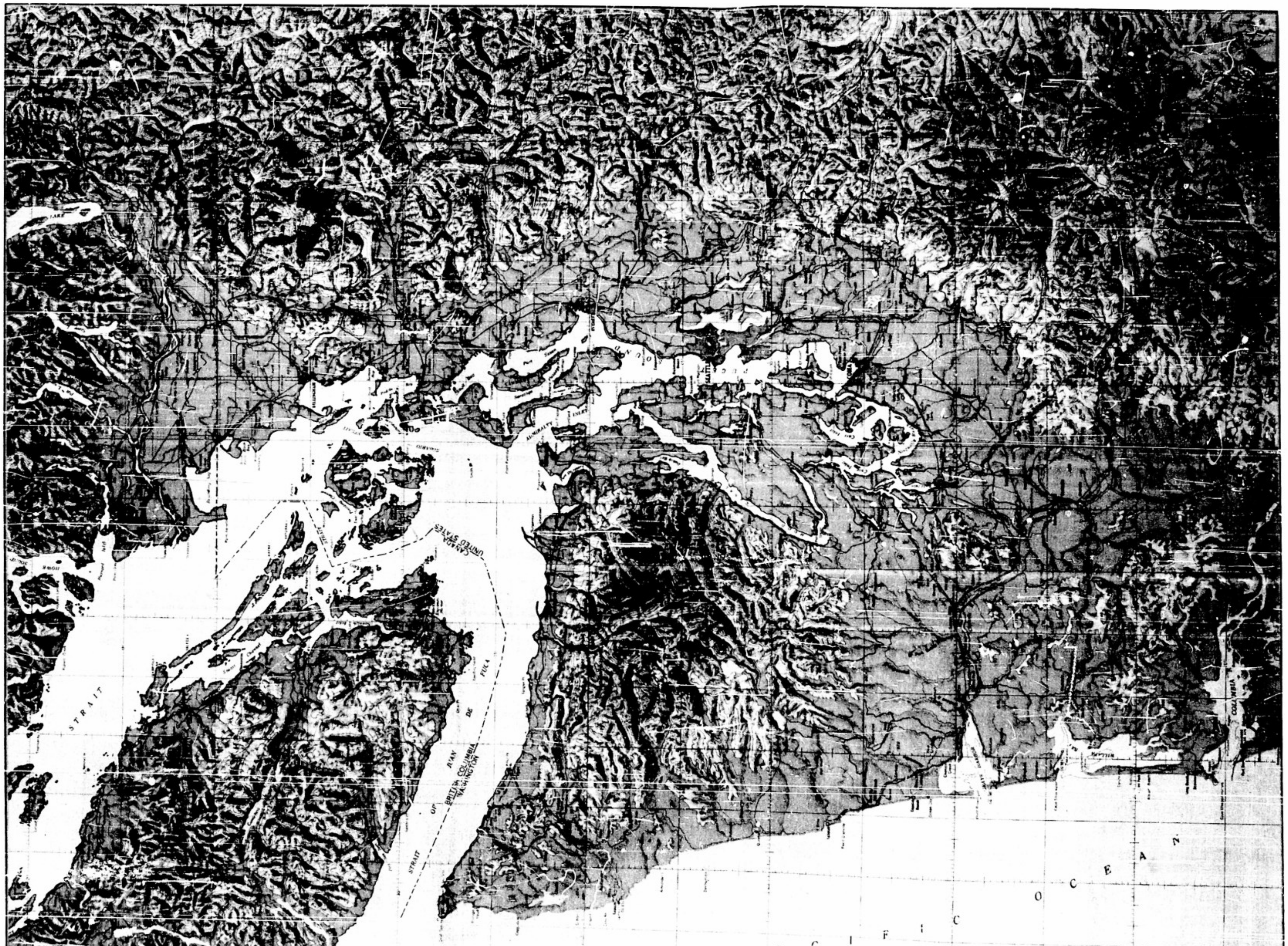

FIGURE 1. Relief map of Northwestern Washington.

THE SURFACE WINDS OVER PUGET SOUND AND THE STRAIT OF JUAN DE FUCA AND THEIR OCEANOGRAPHIC EFFECTS

CHAPTER I

INTRODUCTION

Description of the Area

The area (see Fig. 1) for which the data has been accumulated is comprised of those portions of Washington and British Columbia lying west of the Cascade Mountain range from the Columbia River valley northward to approximately 50 degrees north latitude. The northernmost stations considered are Vancouver, B. C., Entrance Island, near Nanaimo, B.C., and Esteban Point, on the west coast of Vancouver Island. The southernmost are Toledo, Washington, in the Cowlitz Valley and North Head, Washington, on the Pacific coast.

Three main features dominate the region; the Cascade and Coastal mountain ranges and the lowlands which separate them. All three of these features are longitudinal in nature and are directionally oriented north-south.

The Cascade mountain range, forming the eastern boundary of the region, rises to an average height of 5,000 to 6,000 feet with a number of peaks extending to well over 10,000 feet. Several passes breach the range at different points, but the lowest of these, Snoqualmie, is still at an altitude of just over 3,000 feet. Hence, between the

Columbia and Fraser River valleys, the Cascade Range forms an effective block to east-west wind flow.

Between the two mountain ranges, the lowland area extends from the Columbia River valley northward, enclosing the waters of Puget Sound. Farther north it includes the eastern portion of the Strait of Juan de Fuca, the San Juan Islands and Georgia Strait. There are two low-level passageways from this area to the Pacific Ocean, one through the Strait of Juan de Fuca, the other through the Grays Harbor Inlet-Chehalis River valley. Elsewhere the coastal range provides a second barrier to east-west flow.

The Olympic Mountains are the most prominent feature of the Coastal Range. They occupy almost all of the Olympic Peninsula and are roughly triangular in shape. Their western slopes are relatively gradual, leading downward to a narrow coastal plain. The northern and eastern slopes, however, drop sharply from an average height of 5,000 feet to the Strait of Juan de Fuca and Hood Canal. One peak, Mount Olympus, reaches an elevation of 7,954 feet.

South of the Chehalis valley the Coastal Range is again discernible, but with lower elevations. This portion, known locally as the Willapa Hills, is generally from 1,000 to 2,000 feet in height, reaching maximum elevations of 3,000 feet.

North of the Strait of Juan de Fuca, the mountains which comprise almost all of Vancouver Island average about 3,000 feet in height with the higher ranges reaching to 4,000 feet.

The narrow coastal plain extends from the coastal mountain range to the Pacific Ocean. It is present only along the Washington coast.

On Vancouver Island the coastal mountain range extends to the seacoast itself.

General Meteorological Characteristics

The characteristics of the surface winds which occur along the Washington coast and western coast of Vancouver Island are, for the most part, attributable to the circulation around the semi-permanent high pressure cell which dominates the eastern Pacific Ocean.

During the summer months this anticyclone is well developed and centered far enough north to cause prevailing northwesterly flow everywhere along the above-mentioned coasts from North Head, Washington to Esteban Point on the west coast of Vancouver Island.

During autumn the Pacific High begins to retreat southward and weakens considerably. Simultaneously the semi-permanent low pressure center usually centered near the Aleutian Islands begins to intensify and deepen. By midwinter these changing pressure systems have shifted the prevailing flow along the coast to southerly directions, becoming south to southwest at North Head and southeast at Esteban Point.

During the winter period, the area under consideration lies almost directly in the path of the migratory storms which follow the Polar Front. As a result of these storms the entire coast is subject to winds of gale force and above from directions ranging from southeast clockwise to northnorthwest, even though the prevailing flow is well defined as south to southwesterly.

The surface winds which occur over the water and land areas east of the coastal range, however, show sharp contrasts to the general flow,

and indicate the strong topographical effects. Investigation of the wind rose data indicates that the influence of the mountain barriers is equally as important as pressure gradient considerations in determining the direction of these winds.

[1]Reed has made a detailed study of gale winds which occur at the western entrance of the Strait of Juan de Fuca and points out that in a noticeable number of cases of winds over 50 mph at Tatoosh Island the direction of those winds was opposed to the pressure gradient. These were occurrences of easterly gales at that station when the barometric pressure was higher at Tatoosh Island than at Seattle and other points on Puget Sound. At these times, the southerly winds over Puget Sound were sufficiently strong to flow counterclockwise around the Olympics and overcome the pressure gradient through the Strait of Juan de Fuca. In the majority of cases, however, the pressure gradient bebetween the inland basin and the Pacific Ocean was properly oriented to cause east-west flow through the Strait, but by no means sufficiently great to cause the high velocities recorded at Tatoosh Island.

Reed ascribed these winds at that station to the terrain which comprises the shores of the Strait. The steep slopes there narrow funnel-like towards the western end of the Strait. Hence any air mass

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[1]Reed, Thomas L., "Gap Winds in the Strait of Juan de Fuca.", Monthly Weather Review 59: 373-376, 1931.

tending to move westward through the Strait would be subject to the confining effect of this terrain until, at the western end of the Strait the "funneling" or "venturi" effect would result in the high velocities at Tatoosh Island.

The wind roses compiled for the present study indicate that these same topographical effects hold not only for excessively high winds, but also for the wind flow in general over the region.

During the late spring, summer and early autumn months the air masses moving over the area from the Pacific are exceptionally stable, reflecting the influence of subsidence in the dominating high pressure area offshore. As a result, one can expect that winds within these stable air masses will be especially susceptible to the topographic influence of the region.

Availability of Data

Table 1, Description of Stations, lists all of the stations for which summarized surface wind data were obtained. The sources of data are listed in Table 2.

Any investigation of surface wind data over this region is hampered primarily by the scarcity of data, despite the fact that the area is well blanketed by a network of meteorological reporting stations. These stations include those of the United States Weather Bureau, the Civil Aeronautics Authority, Canadian Meteorological Service, military installations and a large number of individual cooperative stations manned by local residents. This latter group of reporting units provides the major portion of the coverage, but unfortunately none are equipped

TABLE 1 DESCRIPTION OF STATIONS

Station	Latitude	Longitude	Elevation (Ft)	Period of Record	Length of period (Yrs)
* Bellingham, Wash.	48 45N	122 29W	159	Jul 50 - Jul 53	3
Entrance Island, B.C.	49 11N	123 50W	35	Jan 22 - Aug 39	18
Esteban Point, B.C.	49 23N	126 32W	---	Jan 22 - Dec 45	24
* Everett, Wash, (Paine AFB)	47 59N	122 12W	598	Nov 38 - Nov 45	6
Garry Point, B.C.	49 06N	123 11W	6	Jan 22 - Apr 41	19
North Head, Wash.	46 16N	124 04W	196	Apr 50 - Dec 52	3
* Olympia, Wash.	47 03N	122 54W	69	Oct 49 - Aug 52	3
* Port Angeles, Wash.	46 07N	123 26W	29	Nov 49 - Aug 52	3
* Sand Point NAS, Wash.	47 41N	122 15W	54	Mar 45 - Dec 52	8
* Seattle-Tacoma Apt., Wash.	46 26N	122 20W	388	Jan 51 - Dec 53	3
Stampede Pass, Wash.	47 17N	121 20W	3963	Jun 50 - Mar 52	2
Tacoma, Wash. (McChord AB)	47 08N	122 29W	300	Aug 40 - Jul 53	13
* Tacoma, Wash.	47 15N	122 26W	165	Duration data only	-
Tatoosh Island, Wash.	48 23N	124 44W	101	Oct 49 - Aug 52	3
Toledo, Wash.	46 29N	122 49W	363	Jul 50 - Jul 53	3
Vancouver, B.C. (Airport)	49 11N	123 10W	22	Feb 36 - Dec 45	11
Vancouver, B.C. (City)	49 17N	123 05W	65	Jan 22 - Apr 42	20
Victoria, B.C.	48 25N	123 19W	228	Jan 22 - Dec 45	24
* Whidbey Island, NAS, Wash.	48 17N	122 39W	---	Apr 45 - Dec 52	8

* High surface wind duration data compiled (1950-1952)

TABLE 2 SOURCES OF DATA

United States Department of Commerce, Weather Bureau

Local Climatological Data -- Yearly Summary
Local Climatological Data -- Monthly Summary, Weather Bureau Form 1001-C

Special Meteorological Summaries -- Weather Bureau Form 1001-C Suppl.

Wind Rose -- Weather Bureau Form 5108B IBM

Surface Weather Observations -- Weather Bureau Form 1130 A, B.

United States Air Force

Surface Weather Observations -- WBAN Form 1130

Flying Weather Wind Rose -- National Weather Records Center, Asheville, N.C.

United States Navy

Surface Weather Observations -- WBAN Form 1130

MARS Climatic Atlas -- National Weather Records Center Asheville, N.C.

Canadian Department of Transport, Meteorological Division

Climatic Summaries for Selected Meteorological Stations Toronto, Ontario, 1948

with wind recording instruments.

As a result, surface wind data are obtainable only from the primary meteorological stations. Even these leave much to be desired with respect to continuity of reports and availability in summarized form.

In preparing wind rose summaries it would be preferred, of course, to have all data summarized over identical periods of time, but the number of stations for which this would be possible is so few as to defeat the primary object of the investigation.

Consequently, summarized data from each station were acquired for whatever period or periods was available in order to obtain the best possible picture at each location. It was felt that increased reliability at individual stations was of greater importance than misrepresentations resulting from unequal periods of summary. This, then, suggests that the final results at each station be weighed as to reliability according to the length of period of summary.

Complete wind rose summaries which include percentages of winds from all points of the compass are available for American stations for recent years only, generally since 1949. Some of these are compiled to 16 points of the compass, others 8. Canadian summaries are available for longer periods, from 1922 through the middle 1940's. The National Weather Records Center at Asheville, N.C., has begun to produce summaries of the desired type since this project was started. Some of these were used for the wind roses given for the Naval Air Stations at Whidbey Island and Sand Point, and the Air Force installations at Paine and McChord Air Force Bases.

The three stations of Seattle, Olympia and Tatoosh Island had complete wind rose data available for periods between October 1949 and August 1953. However, these same stations had available for longer periods data for prevailing wind direction only. An attempt to establish to some extent the representative value of the shorter period was made by means of a comparison of prevailing wind direction for the two periods. The results at each station are tabulated in Table 3.

These comparisons indicate that the recent period of complete data parallels closely the long term averages, at least insofar as the prevailing wind direction is concerned. From this it would seem that one is safe in assuming that for other stations for which no long term data are available, the averages for the recent periods give a fairly accurate representation of what long term summaries would yield.

There were no complete summarized wind rose data available for the Weather Bureau station at North Head, Washington. Here, too, however, summaries were available which represented daily prevailing winds for the period April 1950 through December 1952. These were utilized to compile the wind roses shown in this study for that station. As such, they are not complete, the percentages shown being based on the number of days the prevailing wind was from each direction. It was considered highly desirable to have even an incomplete picture for this station because its location and excellent exposure made it representative of the wind flow from the Pacific reaching that section of the Washington coast.

The compiled surface wind data is shown graphically by means of the usual wind rose polar graphs in Figs. 18 - 29. For all stations

TABLE 3

COMPARISON OF SHORT AND LONG TERM
PREVAILING WIND DIRECTION

MONTH	SEATTLE		TATOOSH ISLAND		OLYMPIA	
	20 yr pd. (8 pts)	Oct 49-Jul 53 (16 pts)	13 yr pd. (8 pts)	Oct 49-Aug 53 (16 pts)	18 yr pd. (8 pts)	Oct 49-Aug 53 (16 pts)
JAN	SE	S	E	E	S	S
FEB	SE	S	E	E	S	S
MAR	S	S	E	W	S	SSW
APR	S	S	W	W	SW	SSW
MAY	S	SSW	W	W	S	SSW
JUN	S	SSW	W	S	SW	SSW
JUL	N	NNW	S	SW	SW	SSW
AUG	N	N	S	S	SW	SSW
SEP	N	N	S	S	SW	SSW
OCT	SE	SSW	E	E	S	SW
NOV	SE	S	E	E	SW	S
DEC	SE	SSE	E	E	S	S

except North Head, the length of the barbs indicates the percentage of the total hourly observations taken in which the wind was reported from each of 8 or 16 different directions. The width of the barbs indicates, within the given ranges, the average velocity of the wind from that direction.

There were no summaries available for any station which would present the type of data desired for the study of the duration of high surface winds. It was necessary, therefore, to compile this data from original hourly wind report records. These original records were readily available from January 1950 to date, and the three year period from January 1950 to December 1952 was chosen as the period for these summaries.

CHAPTER II

ANALYSIS OF WIND ROSE SUMMARIES

December - March

During the winter months the prevailing wind off the southern Washington coast is south to southwest. Northward it backs gradually to southeast off Esteban Point, B.C.

The prevailing flow over the Puget Sound area is also southerly. These latter winds approach the Sound area from the south through the Cowlitz Valley past the reporting station at Toledo, Washington, and from the Pacific Ocean through the Chehalis River valley. An investigation of the data from North Head shows a higher percentage of easterly winds which are due, probably, to the localized effects of the Columbia River valley. However, the higher velocities at that station are found with the south and southwest winds, and it seems probable that for these winds the Willapa Hills do not constitute an effective barrier to onshore flow from these directions.

The southerly flow over the Sound is indicated as far north as Bellingham, but the data for the Georgia Strait and Strait of Juan de Fuca areas show sharp contrasts. Winds at the Vancouver stations are predominantly easterly, reflecting, no doubt, the effect of the Fraser River valley. Here again, however, a considerable percentage of winds with higher velocities is from southerly directions, suggesting that a net flow of air may pass northward up Georgia Strait.

The data from Entrance Island and Victoria, however, do not allow the assumption that this simple picture persists across the width

of the Strait. The directions and highest velocities at Entrance Island show a definite predominance from the east and northeast. Victoria shows a well defined predominance of northerly winds. Both these stations are well exposed and may be considered representative. Their data indicate that for at least a considerable portion of the time there is a reversal of flow across Georgia Strait and the San Juan Islands, with the further possibility of a frequent closed, counterclockwise circulation over the Strait near the latitude of Vancouver.

The flow in the Strait of Juan de Fuca is apparently not always the simple "east or west" picture sometimes assumed. The presence of the funnel or Venturi effect suggested by Reed seems the most logical explanation of the strong easterly winds at Tatoosh Island. The data from Port Angeles, however, show higher percentages of winds from the southsouthwest to west. This would suggest that frequently the wind direction is reversed between Port Angeles and Tatoosh Island.

It seems likely that this unexpected feature is also related to the configuration of the Olympic mountain range along the southern shore of the Strait. The slope of these mountains is very steep along the entire length of the Strait and would serve to confine at least the lower layers of the easterly gales which pass Tatoosh Island.

It would appear, then that for a considerable portion of the time the north wind at Victoria turns westward into the Strait, but encounters the confining Olympic range only at points west of Port Angeles. It is suggested that a division of the flow takes place at some point west of this station, the major stream passing westward through the Strait to form the easterlies at Tatoosh, while a much

weaker stream is deflected eastward to furnish the westerly winds at Port Angeles.

The average location of this suggested point may perhaps be indicated by the precipitation pattern of the area. United States Weather Bureau records, and precipitation data compiled by Gerlach[2] indicate that the "rain shadow" created by the Olympic Mountains over Port Angeles and most of the Puget Sound area breaks sharply just west of Port Angeles. Ten miles west the precipitation during the winter period is about double that at Port Angeles, while at Clallam Bay, 25 miles farther along the Strait, it is more than triple that amount.

This precipitation increase is usually explained by the fact that the Olympic mountains decrease sharply in elevation about 20 miles west of Port Angeles, averaging about 1500 feet in height from there westward. This permits the moist southwesterly flow from the Pacific to carry much of its moisture across the mountains on to and over the Strait. However, if the northerly flow which passes Victoria and crosses the Strait were to encounter the abrupt slopes of the Olympics at this point, one would also expect a precipitation increase there as a result of orographic lifting of the onshore winds.

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[2]Gerlach, Arch D. "Precipitation of Western Washington", Ph.D. Dissertation, 1943 Library, University of Washington, Seattle, Washington.

Therefore, although the region of sharp precipitation increase is probably due primarily to the change in elevation of the Olympics at that point, at least a portion of that increase may well be due to orographic lifting of north or northeast winds which first encounter the slopes of the Olympics in this region.

The fact that the prevailing winds at Port Angeles are westsouthwest to southwest, rather than due west or westnorthwest may also indicate that some of the air which crosses the mountains west of Port Angeles passes eastward along and down the slopes of the higher portions of the Olympic Mountains to the east, passing Port Angeles from the prevailing direction.

The regional flow pattern just described is shown graphically in Fig. 2. This pattern represents, of course, the prevailing wind flow over the region, and is by no means meant to describe simultaneous conditions at all times. However, it could logically be expected to exist frequently under recurrent meteorological situations. An example was found to exist on January 24, 1951, and the wind flow pattern and isobaric configuration for that and the following days are depicted in Figs. 3 - 4.

On these days the region was under the influence of a low pressure center located about 500 miles due west of Tatoosh Island. On the 24th, the easterly winds at Tatoosh Island were at a maximum velocity at the surface, and merged gradually into the southwesterly flow at 6,000 feet. The observations at Port Angeles seemed to indicate that the point of divergence previously suggested was in the near vicinity

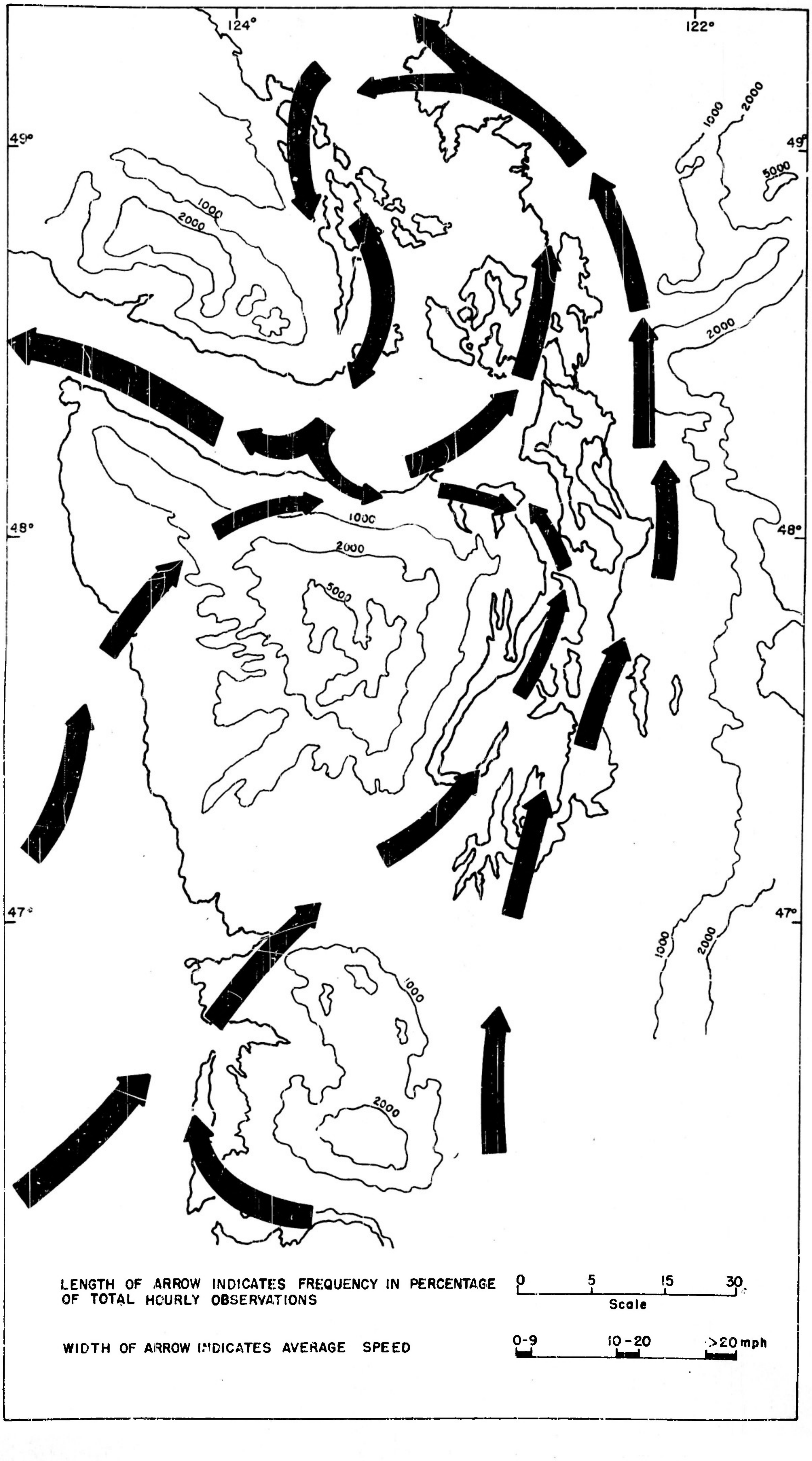


FIGURE 2. Prevailing surface winds: October - March.

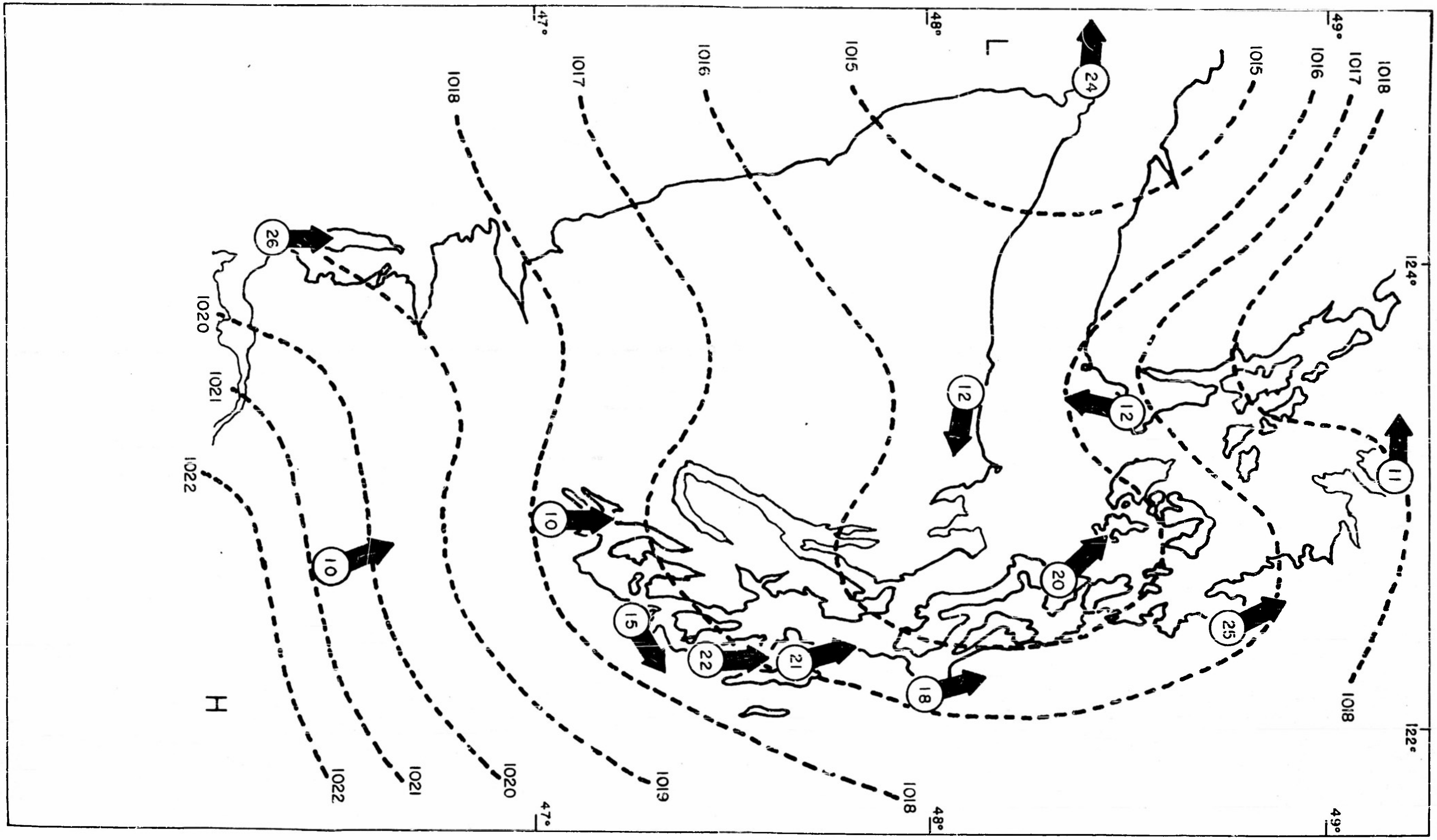


FIGURE 3. Surface wind flow 0400 PST, 24 January 1951. Dashed lines indicate barometric pressure in millibars. Arrow indicates surface wind direction. Circled number represents surface wind velocity in miles per hour.

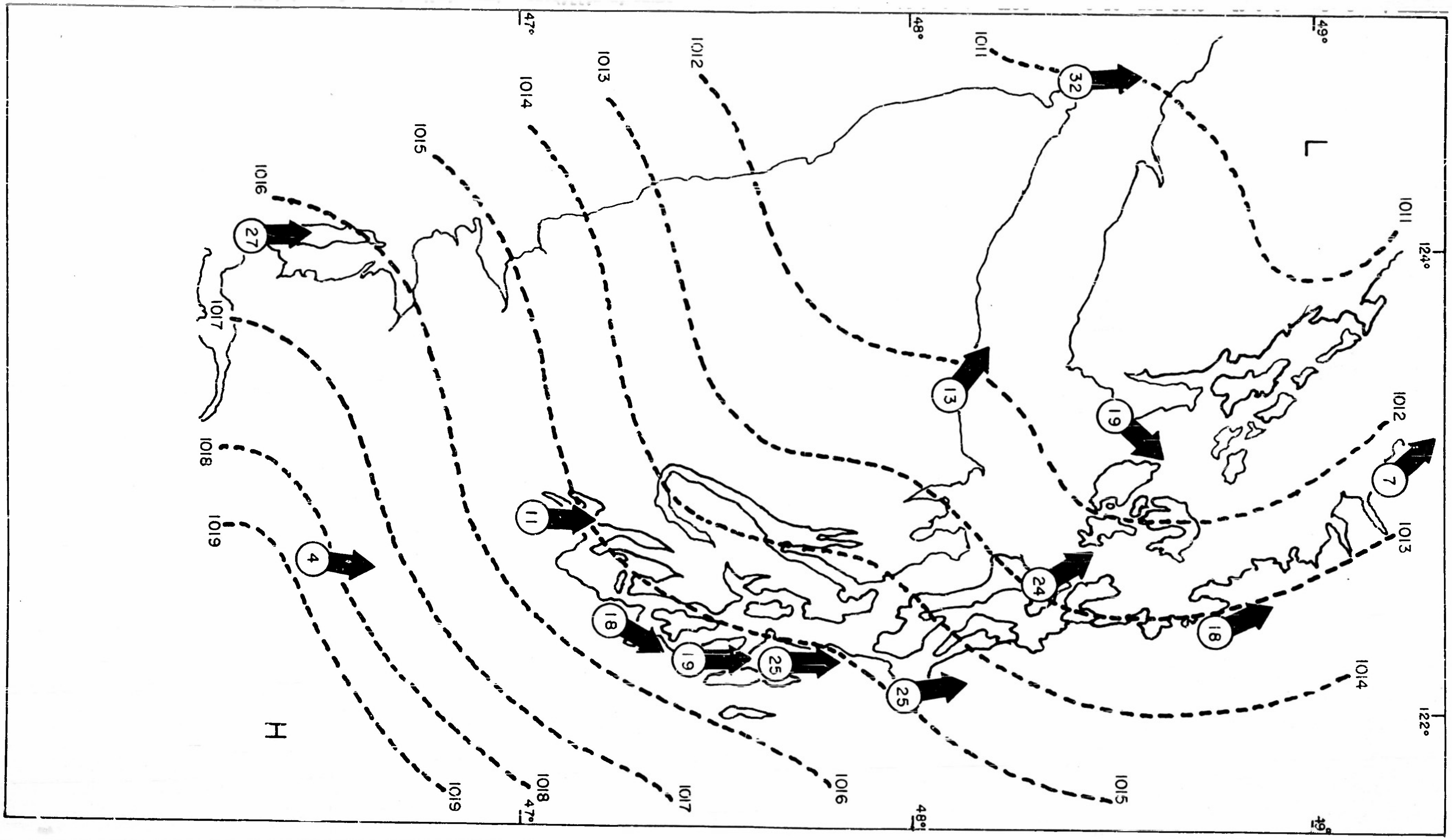


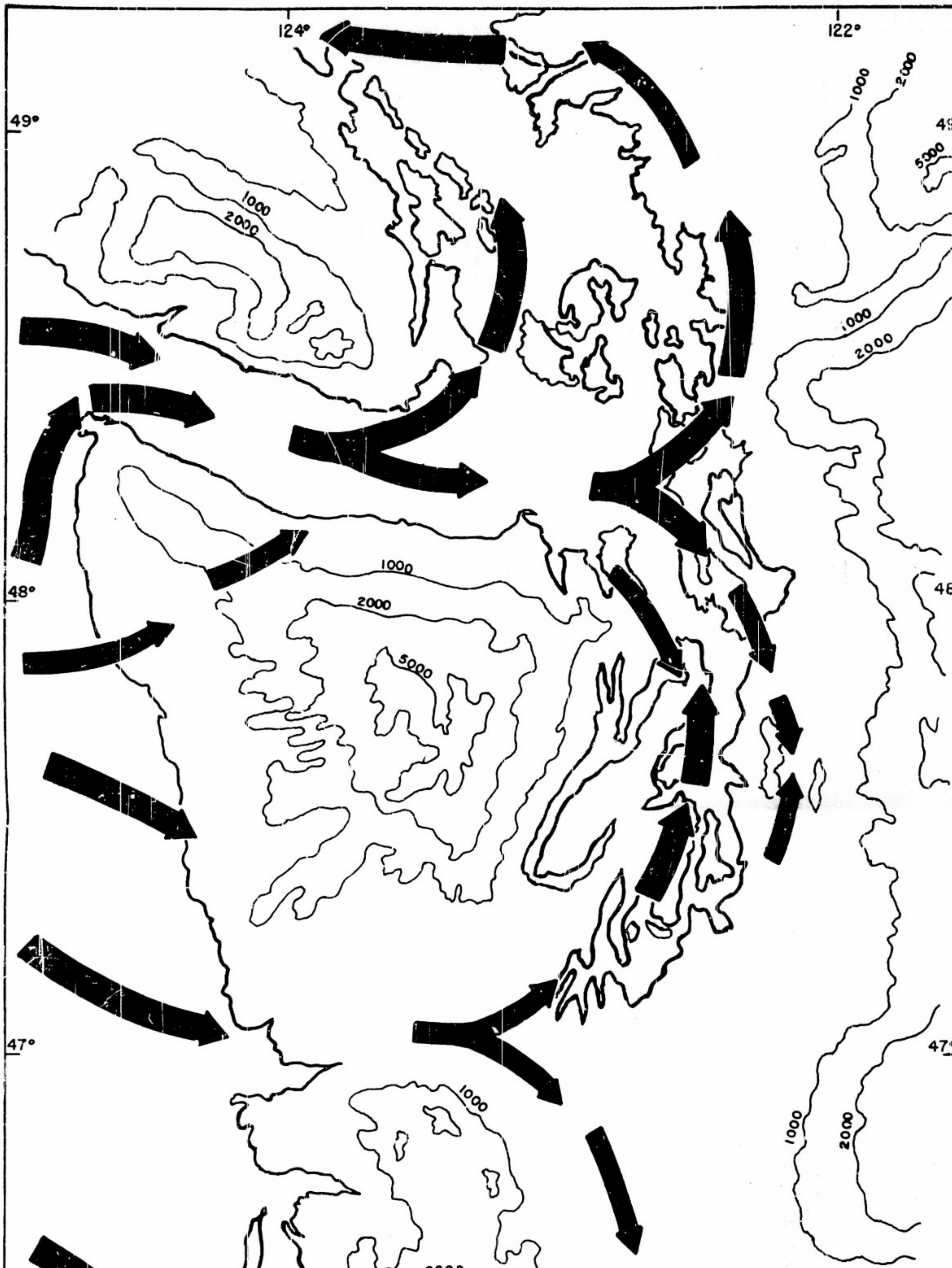
FIGURE 4. Surface wind flow 0400 PST, 25 January 1951. Dashed lines indicate barometric pressure in millibars. Arrow indicates surface wind direction. Circled number represents surface wind velocity in miles per hour.

of that station, since the winds there changed erratically between southwesterly and northeasterly directions throughout the day, sometimes from hour to hour.

With the continued approach of the low center, however, the easterly flow at Tatoosh was apparently overcome by the stronger southerly winds associated with the storm center. On the 25th, the wind at Tatoosh veered to the south and increased in velocity to 32 mph. This disappearance of easterly flow in the Strait was reflected also at Port Angeles and Victoria, where complete reversals of wind direction were observed. There was no indication at this time, therefore, of the closed circulation over Georgia Strait, and apparently the surface flow was southerly over all of Puget Sound and Georgia Strait, reinforced by an influx of air from the southwest over the lower ranges of the Olympics west of Port Angeles.

April - May

During the spring months the northward migration of the Pacific High is indicated (see Fig. 5) by the prevailing winds at North Head, which veer from south to northwest and those at Tatoosh Island, which lose their predominantly easterly characteristics and veer to the south and eventually west. The prevailing flow over the southern portions of Puget Sound, however, remains predominantly southerly, while that in the Cowlitz Valley past Toledo becomes northerly. This seems to indicate that a net influx of air passes eastward through the Chehalis River valley and diverges, one stream continuing southeastward past Toledo, the other moving northward around the Olympics and over Puget Sound.



LENGTH OF ARROW INDICATES FREQUENCY IN PERCENTAGE OF TOTAL HOURLY OBSERVATIONS

0 5 15 30
Scale

WIDTH OF ARROW INDICATES AVERAGE SPEED

0-9 10-20 >20 mph

FIGURE 5. Prevailing surface winds: April - May.

The reports on the Strait of Juan de Fuca also indicate a net flux into the Strait. The winds at Tatoosh Island, Port Angeles and Victoria are predominantly westerly, while those at Whidbey Island veer from southeast to southwest and west. The data at Everett develop a definite northerly preference, suggesting that a zone of convergence occurs frequently between air moving from the Strait of Juan de Fuca southward over Admiralty Inlet and that flowing northward from the influx through the Chehalis River valley.

The Bellingham wind rose, however, shows prevailing winds from south to southeast throughout the period. This suggests that the flow through the Strait of Juan de Fuca diverges upon reaching the Cascade Range, one stream flowing to the north past Bellingham, the other south to explain the prevailing northerly component at Everett.

June - September

During the summer months the general surface flow over the area (see Fig. 6) becomes weaker at all stations except Port Angeles, where a strong late-afternoon diurnal effect causes a maximum average velocity in July.

Relatively, however, the westerlies through the Strait of Juan de Fuca become stronger and prevailing northerly winds progress further southward over Puget Sound. By September this northerly flow is established as far south as Tacoma. At that time Tacoma and Olympia show a high percentage of calm winds, while recorded surface winds are almost equally distributed between those with southerly and northerly components. Thus the zone of convergence of prevailing winds apparently

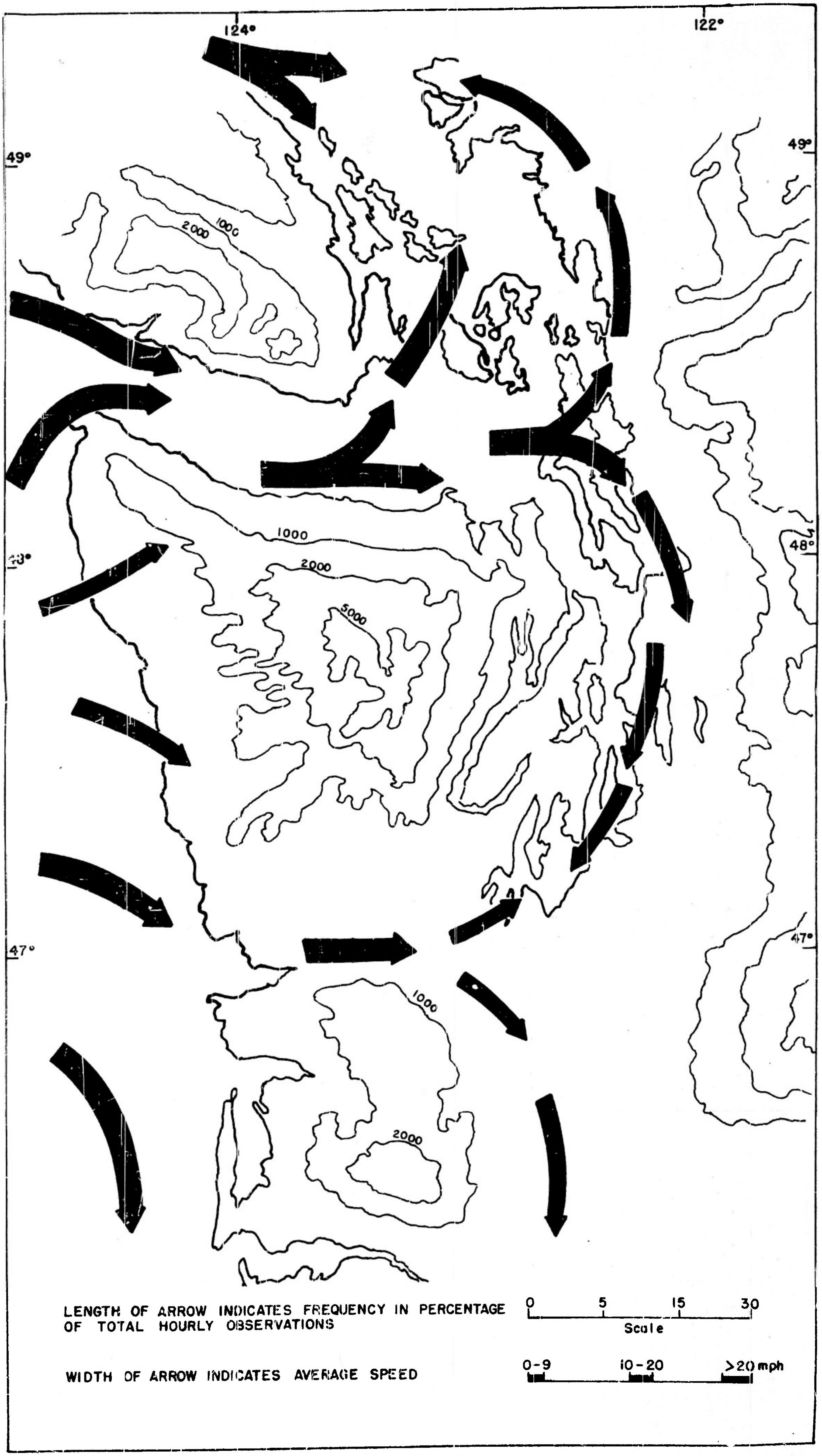


FIGURE 6. Prevailing surface winds: June - September.

progresses southward over the Sound, reaching the Tacoma-Olympia vicinity by late summer. The winds at Toledo maintain a well defined northerly component, indicating that there is probably still a net influx of air through the Chehalis River Valley.

The data from Port Angeles, Whidbey Island and Victoria still indicate a well defined prevailing flow through the Strait of Juan de Fuca from west to east, but give no apparent indication as to why the prevailing wind at Tatoosh Island becomes definitely south. This unexpected feature is especially puzzling in view of the fact that the prevailing winds at North Head and Esteban Point are strongly defined as north and northwesterly from June through August.

A check of offshore prevailing winds as given in the Climatic Atlas of the Oceans[3] showed these also to be from the westnorthwest and northwest. By September the reports from Esteban Point and North Head begin to show a sizable percentage of southeast and south winds, which match more closely the picture at Tatoosh Island, but this still does not account for the sharp difference during the previous months. Local topographic effects are unlikely, since the station at Tatoosh Island is well exposed, and it would seem especially unlikely that it would be protected from west and northwest flow to such a great extent.

A logical explanation may be that here again, a Venturi effect takes place at the entrance to the Strait. As previously noted, air

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[3]United States Department of Agriculture: "Atlas of Climatic Charts of the Oceans", United States Weather Bureau, Washington, D.C., 1938.

passing into the Strait at this time of year is usually exceptionally stable. This would further increase the likelihood of favorable conditions for the suggested Venturi effect.

A specific example is again presented to indicate that the prevailing wind pattern just described may exist simultaneously over the region.

The surface wind flow and isobaric configuration for 23 July 1950 are shown in Fig. 7. The wind at Tatoosh Island is from the south, opposing the weak pressure gradient. The strong diurnal effect is noted at Port Angeles, and the divergence of this stream is indicated by the southerly wind at Bellingham and the northerly flow past Everett. In this case the northerly flow, apparently influenced by the pressure pattern is present over the entire Sound, and continues southward through the Cowlitz Valley. Without data from the Grays Harbor area, it cannot be determined whether air passed eastward or westward through the Chehalis River valley.

It is worth noting here that the United States Weather Bureau established a reporting station at Hoquiam, Washington, on Grays Harbor, in 1953. Accumulated data received in the future from this station may give excellent indications of the type of flow in the Chehalis River valley at all times.

October - November

During the autumn and early winter season, the prevailing surface flow returns rapidly to that described for the winter months. Noteworthy is the fact that the prevailing northerly flow over Puget Sound

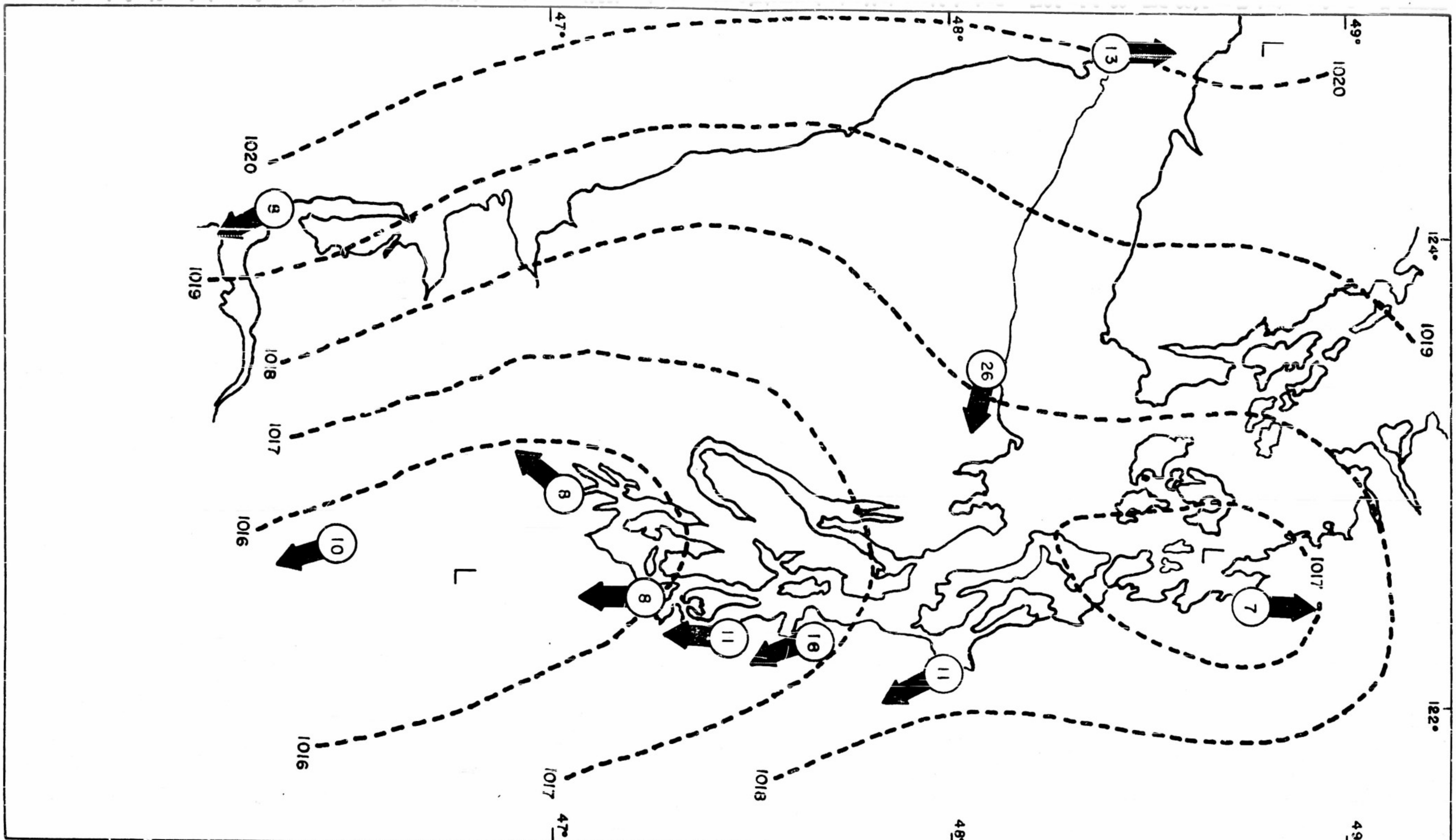

FIGURE 7. Surface wind flow 1600 PST, 23 July 1951. Dashed lines indicate barometric pressure in millibars. Arrow indicates direction of surface wind. Circled number represents surface wind velocity in miles per hour.

deteriorates much more rapidly than it developed. The return of the tendency for prevailing easterly flow at Tatoosh Island apparently heralds the rapid dissolution of the pattern necessary to maintain the northerly flow into the Sound.

CHAPTER III

FREQUENCY AND DURATION OF HIGH SURFACE WINDS FOR THE PERIOD JANUARY 1950 THROUGH DECEMBER 1952

Evaluation of Data

It is appropriate to discuss briefly the representative value of the accumulated data on high surface winds before descriptive and quantitative comparisons are made.

The periods of summary are identical for the eight stations chosen. It should be borne in mind, however, that for all stations except Tacoma, the hourly wind reports from which the data were derived record the wind direction and speed only at the time the observer was making his observation. Theoretically, then, for 55 minutes out of each hour the wind could be other than that recorded. However, it is believed that over as large a series of observations as are considered here, these discrepancies should smooth out to an extent that would admit the observed readings as representative. The chance of false summaries being formed would seem to be even less likely in consideration of extended periods of high velocities, when the direction of flow would be more unlikely to vary over large ranges of the compass.

The data for Tacoma were derived from continuous recording instruments, and represent true prevailing directions and velocities for the hour preceding the time of the hourly observation.

The different elevations at which the stations are located must also be considered in evaluating the high surface wind data, since our primary interest is in the wind flow over the water surfaces of the

region. These elevations range from 54 feet above mean sea level at the Sand Point Naval Air Station to almost 600 feet at Everett. Therefore, the extent to which the winds at these stations represent the actual direction and velocity over nearby waters is determined to a great extent by the detailed topography of the immediate area.

The high surface wind data are presented in graphical "rose" form in Figs. 30 - 41. The graphs are drawn to represent the number of separate occurrences of surface winds of the designated velocity ranges which occurred during the three year period. Two considerations dictated the assignment of 18 mph as the limiting minimum in defining "high" surface winds. Since a determination of maximum wind waves on Puget Sound was to be made, the value of 18 mph was chosen as the minimum velocity which could result in the formation of waves of 6 feet in height on the longest "fetch" possible on the Sound (34 miles). In addition, the 18 mph value proved to be about the lowest which would be practicable in the compilation of data and assignment of "duration" and "occurrence" limits. The average and maximum durations are given in numeral form on each directional segment of the graphs.

The use of these directional segments, rather than individual directions was chosen after preliminary investigation of the data revealed that surface winds with extended periods of above average velocities were in nearly all cases confined to relatively narrow ranges of the compass at each station. This would, of course, be expected, in view of the longitudinal topography of the region. Furthermore, a representative "duration" could not be derived if small variations in direction were to be considered as separate "occurrences".

The graphs distinctly show the confining effects of the topography on strong surface wind flow over the entire area. Over Puget Sound as far north as the Whidbey Island station the Olympic Mountains permit such flow to persist only from southerly or northerly directions. The data at Bellingham indicate that here such winds are observed within ranges from north to northeast and east to southwest. The absence at this station of any extended periods of high surface winds from westerly directions is somewhat surprising, in view of the free approach from that direction from the eastern coast of Vancouver Island.

The Port Angeles graph, however, reveals that high surface winds may occur at that station from all quadrants except that from southeast to southwest, which is completely blocked by the Olympics. Farther westward on the Strait, these winds are in all probability confined by the topography to easterly and westerly directions only.

A second series of graphs (see Figs. 8 - 10) is presented to reflect the seasonal frequency and duration relationships at each station. These summarize all occurrences noted, without regard to direction. As would be expected they show maximum frequency and duration in the winter period of more frequent storm passages. An exception to this pattern is found at Port Angeles, where the diurnal effect in the summertime causes a duration and frequency maximum in July.

<u>December - March</u>

During the winter months the majority of high surface winds over the Puget Sound area are from southerly directions and are a reflection of the approach of frequent storms from the Pacific. The maximum

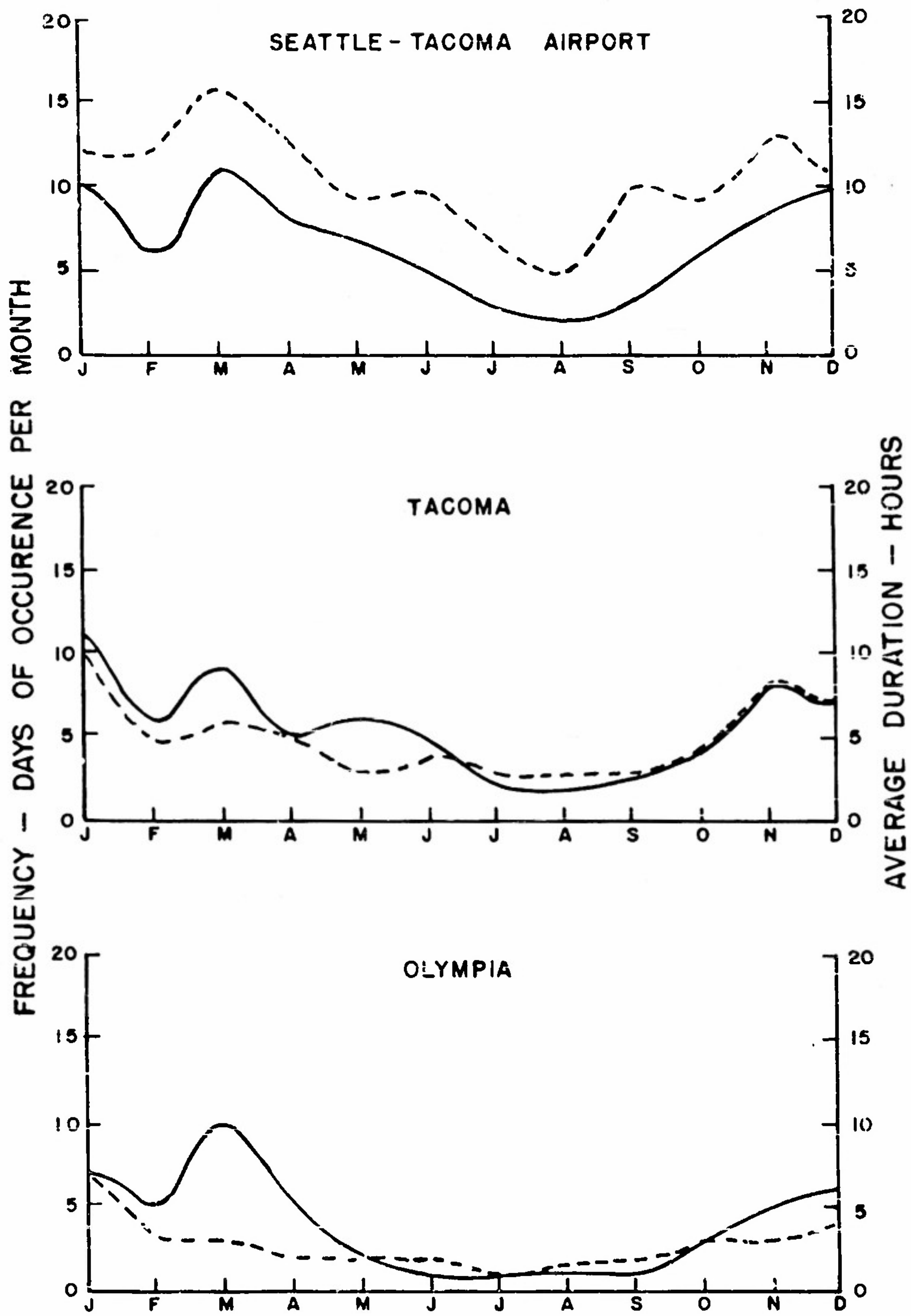

FIGURE 8. Frequency and duration of surface wind velocities over 15 mph (all directions). Solid lines represent frequency in days of occurrence per month. Dashed lines represent average duration in hours.

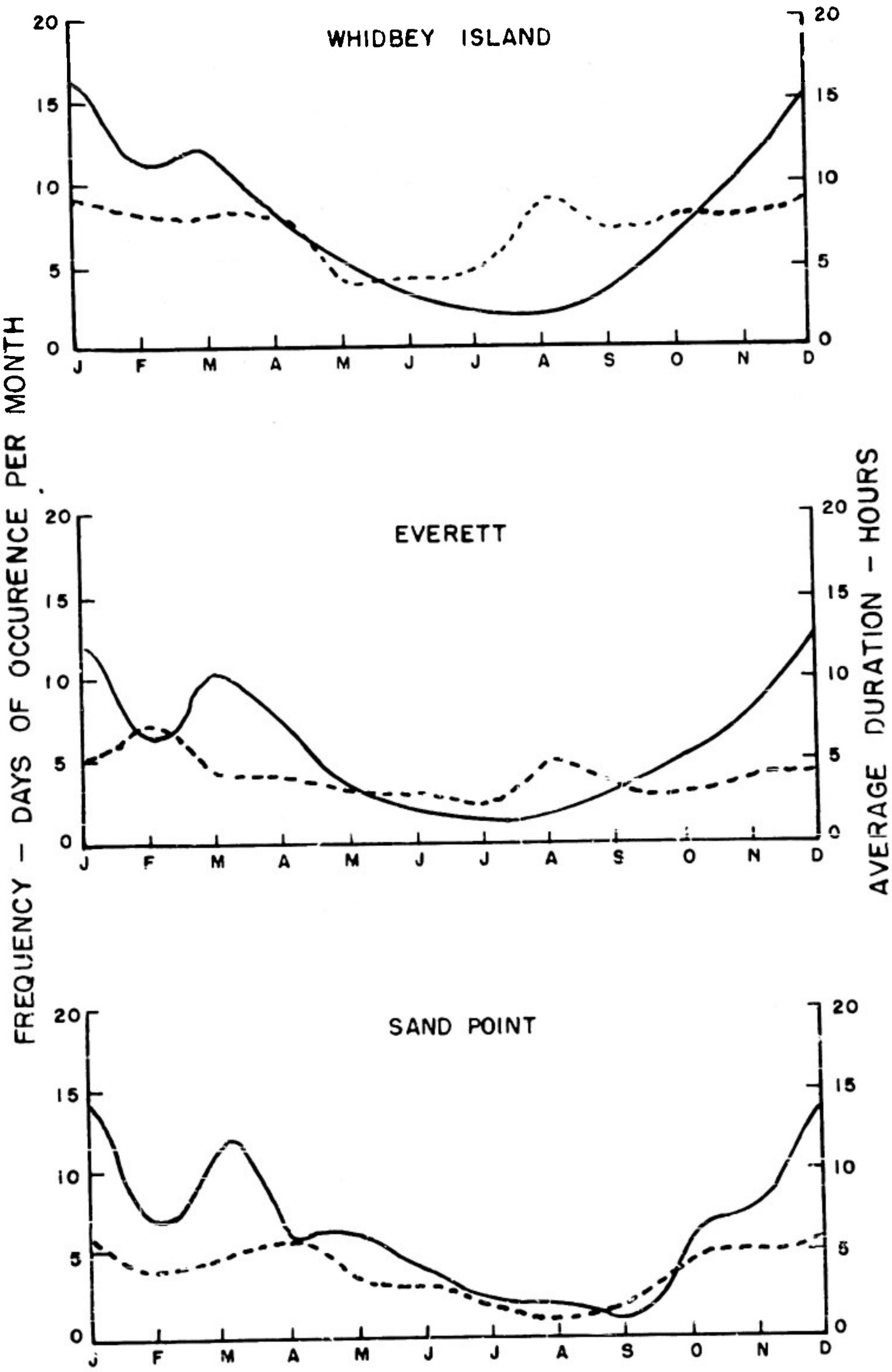

FIGURE 9. Frequency and duration of surface wind velocities over 18 mph (all directions). Solid lines represent frequency in days of occurrence per month. Dashed lines represent average duration in hours.

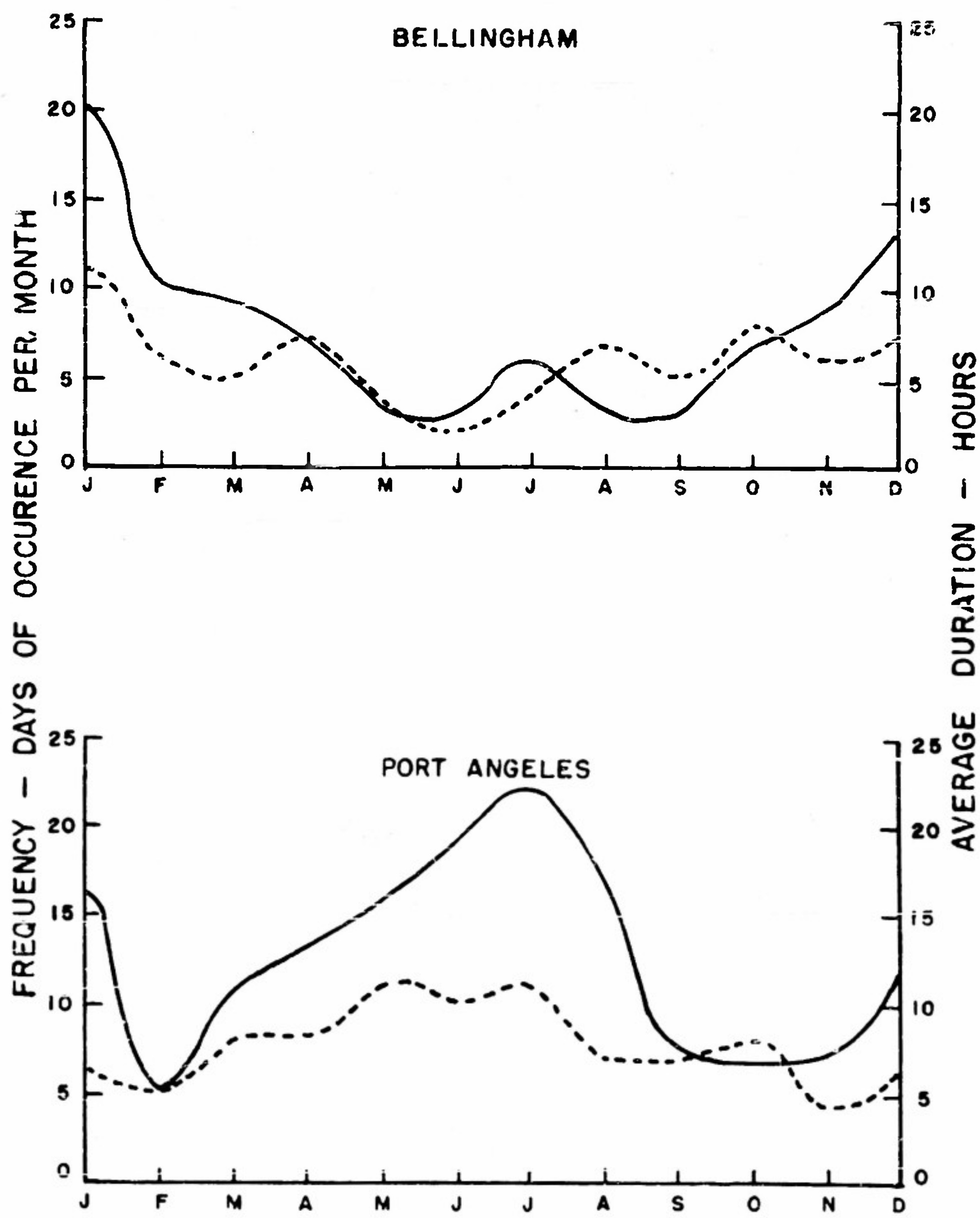

FIGURE 10. Frequency and duration of surface wind velocities over 18 mph (all directions). Solid lines represent frequency in days of occurrence per month. Dashed lines represent average duration in hours.

frequency generally occurs during January and March, with a noticeable decrease in February. The frequency of the winds increases progressively northward over the Puget Sound area, reaching an average maximum of 13 days per month at Whidbey Island in December. The frequency at Bellingham was slightly lower than that at Whidbey Island.

During these periods of high southerly winds over the Puget Sound area, the winds in the Strait of Juan de Fuca may be either easterly or westerly, their direction determined by the position of the storm center.

An example of these conditions was noted on January 2, 1951. A deep low center (979.3 mb.) had developed rapidly off the Pacific coast and moved inland across Vancouver Island and the Puget Sound area. Lowest pressure was observed at Port Angeles, and pressure readings at other stations indicated that the storm center crossed almost directly over the eastern end of the Strait of Juan de Fuca at 1600 PST.

The flow patterns prior to and after the passage of the storm center are shown in Figs. 11 - 13. The strong flow in this case remained southerly over most of the Puget Sound area throughout the duration of the storm, while that in the Strait of Juan de Fuca reversed from easterly to westerly with the passage of the storm center. As indicated by the data from Everett, this reversal of direction brought strong northerly winds to the northern portion of the Sound for a short period of time, and it is interesting to note that for more than 4 hours there were converging surface winds of 25 to 30 mph from the northwest at Everett and the southsouthwest at Seattle-Tacoma airport.

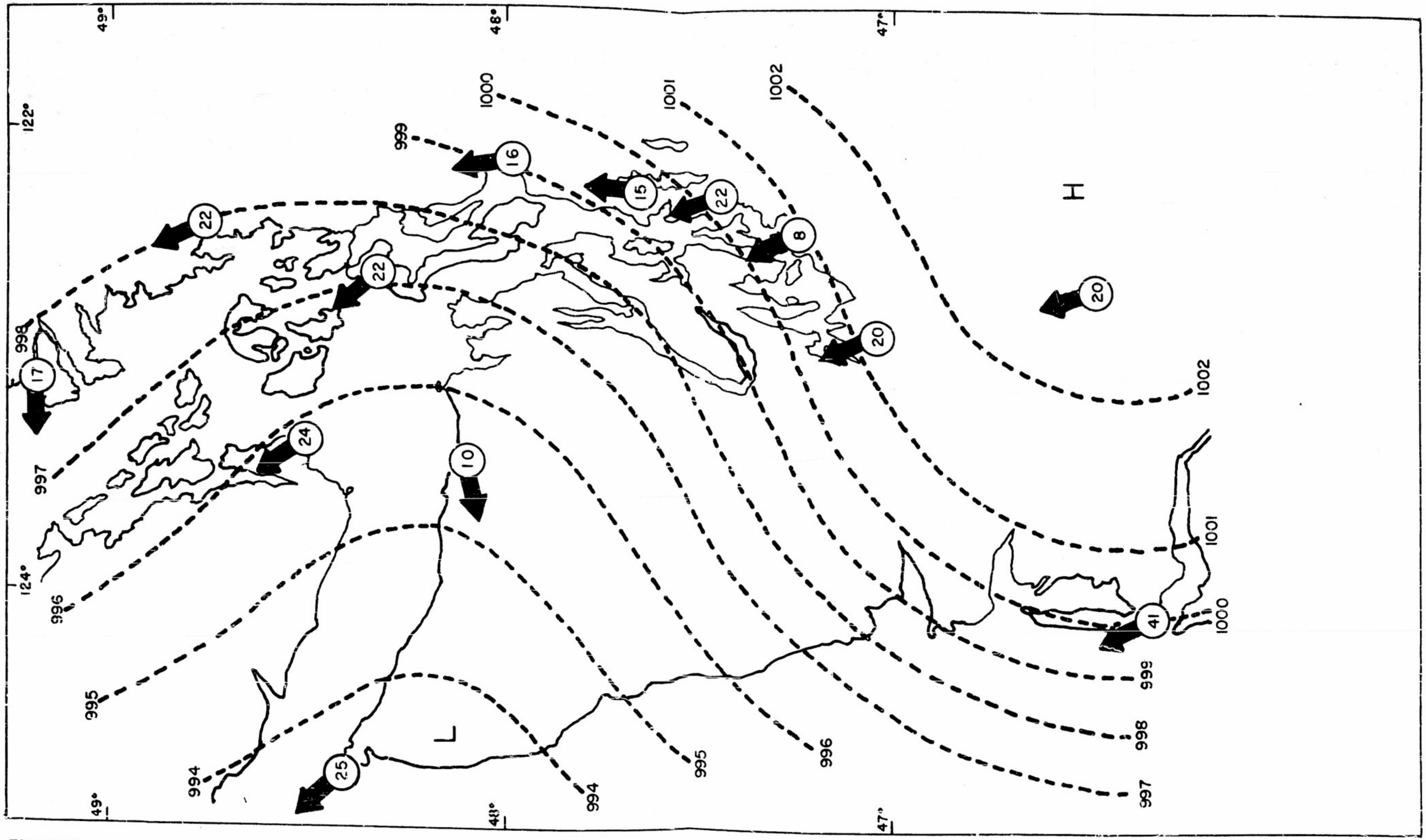

FIGURE 11. Surface wind flow 0400 PST, 2 January 1951. Dashed lines indicate barometric pressure in millibars. Arrow indicates surface wind direction. Circled number represents wind velocity in miles per hour.

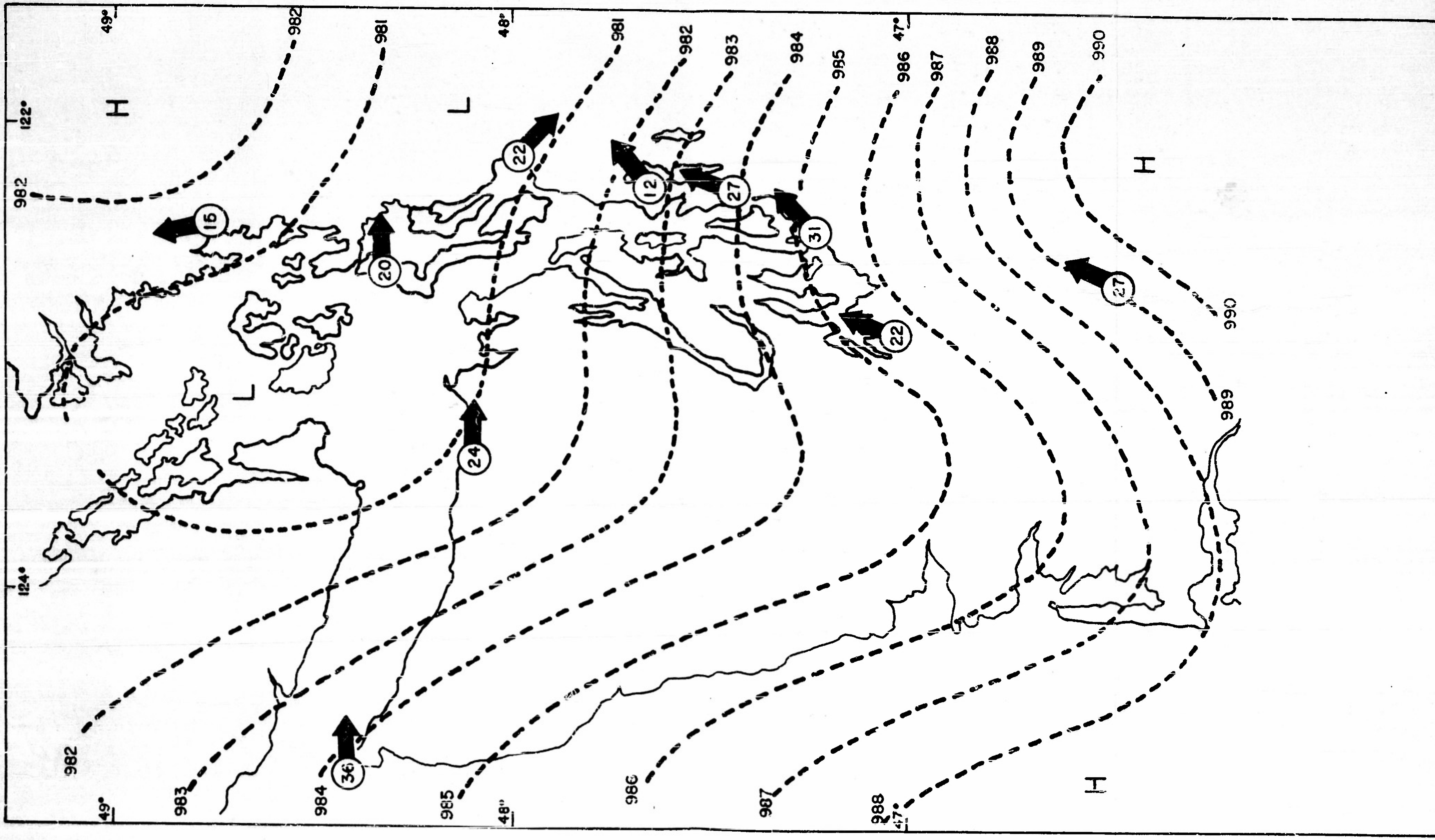

FIGURE 12. Surface wind flow 1800 PST, 2 January 1951. Dashed lines indicate barometric pressure in millibars. Arrow indicates direction of surface wind. Circled number represents surface wind velocity in miles per hour.

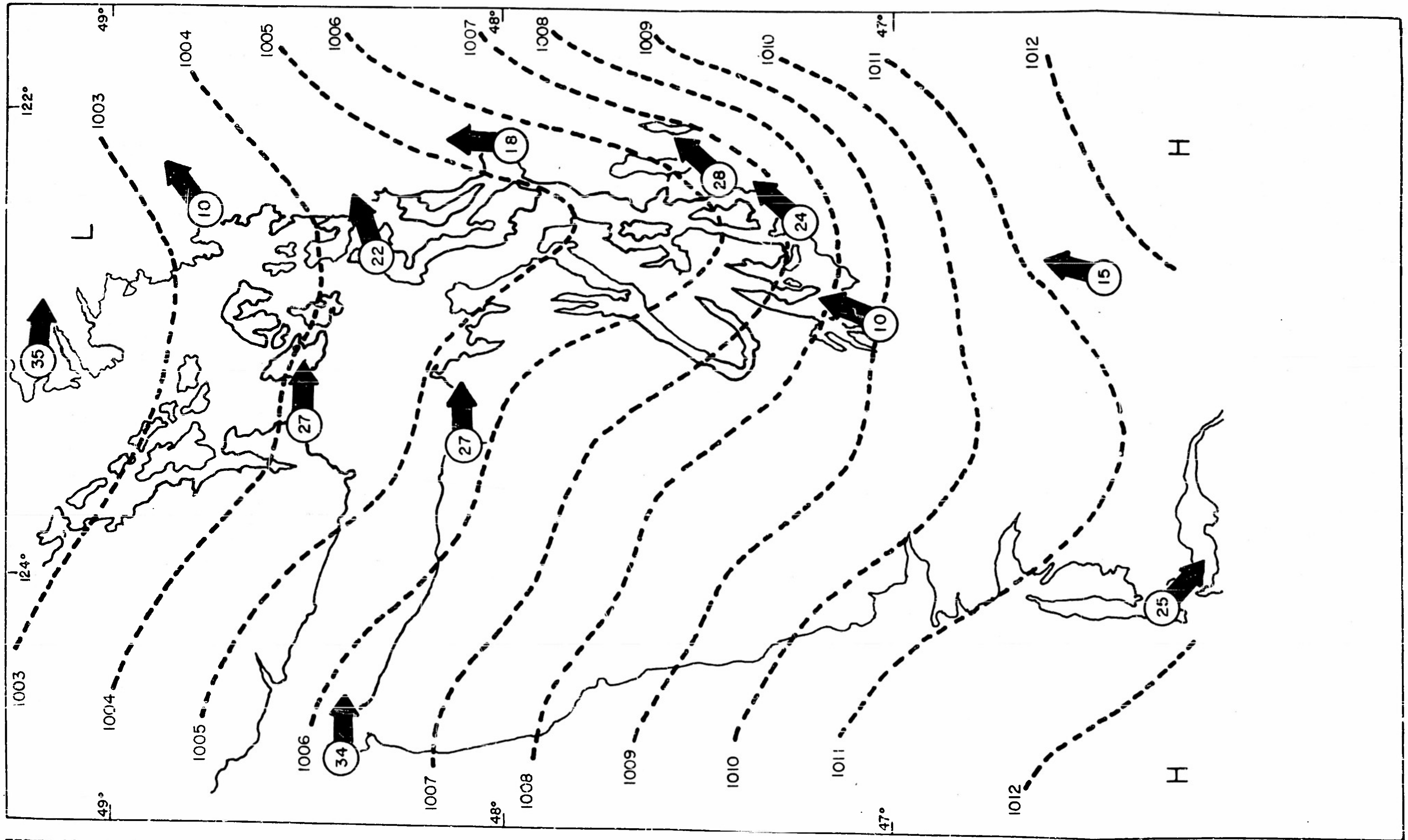

FIGURE 13. Surface wind flow 0400 PST, 3 January 1951. Dashed lines indicate barometric pressure in millibars. Arrow indicates direction of surface wind. Circled number represents surface wind velocity in miles per hour.

The periods when high surface winds from northerly components occur over the entire Sound Basin appear in most cases with the passage of similar storms inland.

Their lower frequency of occurrence, however, seems to indicate that in many cases these northerly winds do not appear at all, and that southerly winds persist over the Sound prior to and after the storm passage. This can probably be attributed to the fact that the low pressure centers usually pass inland north of the area, thus providing pressure gradients which favor southerly flow over the Sound. The flow pattern shown for 0400 PST January 3, 1951 would seem therefore, to be the most frequent type to be expected with these storm passages. However, the duration data indicate that, unlike the pattern of January 2, 1951, they generally persist over the Sound for approximately the same periods of time as those from southerly directions. At Bellingham and Port Angeles their average duration exceeds that of the southerly and westerly streams. The data from Olympia, however, show only one occurrence of high northerly winds in the three year period. This would lead to the assumption that the high surface winds passing over the Sound from the north either decrease rapidly upon reaching the Chehalis River valley or are restricted to a narrow path along the western slopes of the Cascades. It should perhaps be pointed out here that the average duration of 15 hours shown for Tacoma in January is not representative, but is rather a reflection of the particular storm of January 27, 1951 which is discussed below.

Another, much less frequent type of strong northerly flow over the region may occur when a cold, dry air mass from the interior of

Canada crosses the Rocky and Cascade mountains and reaches the Pacific coastal area. A case of this type occurred on January 26-28, 1951, (see Fig. 14). A cold, deep high pressure area had persisted over northwestern Canada for 4 days. An intense low pressure center developed in Wyoming and moved eastward. The strong circulation around the northern quadrant of this storm was sufficient to move the continental air mass accross the Rocky Mountains and onto the western slopes of the Cascade Range.

Unusually strong and persistent flow resulted over the entire Puget Sound Basin. At Bellingham, surface winds over 18 mph persisted for 54 hours, during which time the velocities were maintained over 30 mph for 46 hours, and over 40 mph for a period of 27 hours. Strong gusts to over 50 mph occurred on the 26th, 27th and 28th, and on the 27th frequently exceeded 70 mph. The cold, dry flow was accompanied by clear skies and the barometric pressure reached a maximum of 1041.3 millibars.

A lack of high velocities was noted at Whidbey Island and Olympia. At other stations high velocities persisted for 26 hours at Port Angeles where they did extensive damage, for 12 hours at Everett, Sand Point NAS and Seattle-Tacoma airport, and for 36 hours at Tacoma.

The topography of Whidbey Island would seem to be the explanation for the lack of high velocities at the Naval Station there, which is located almost at sea level, and is protected from the northeast to west by hills averaging 200-300 feet in height, with some rising to over 500 feet. The lack of high winds at Olympia, however, probably indicated that the major portion of the cold air flow parelleled the Cascade

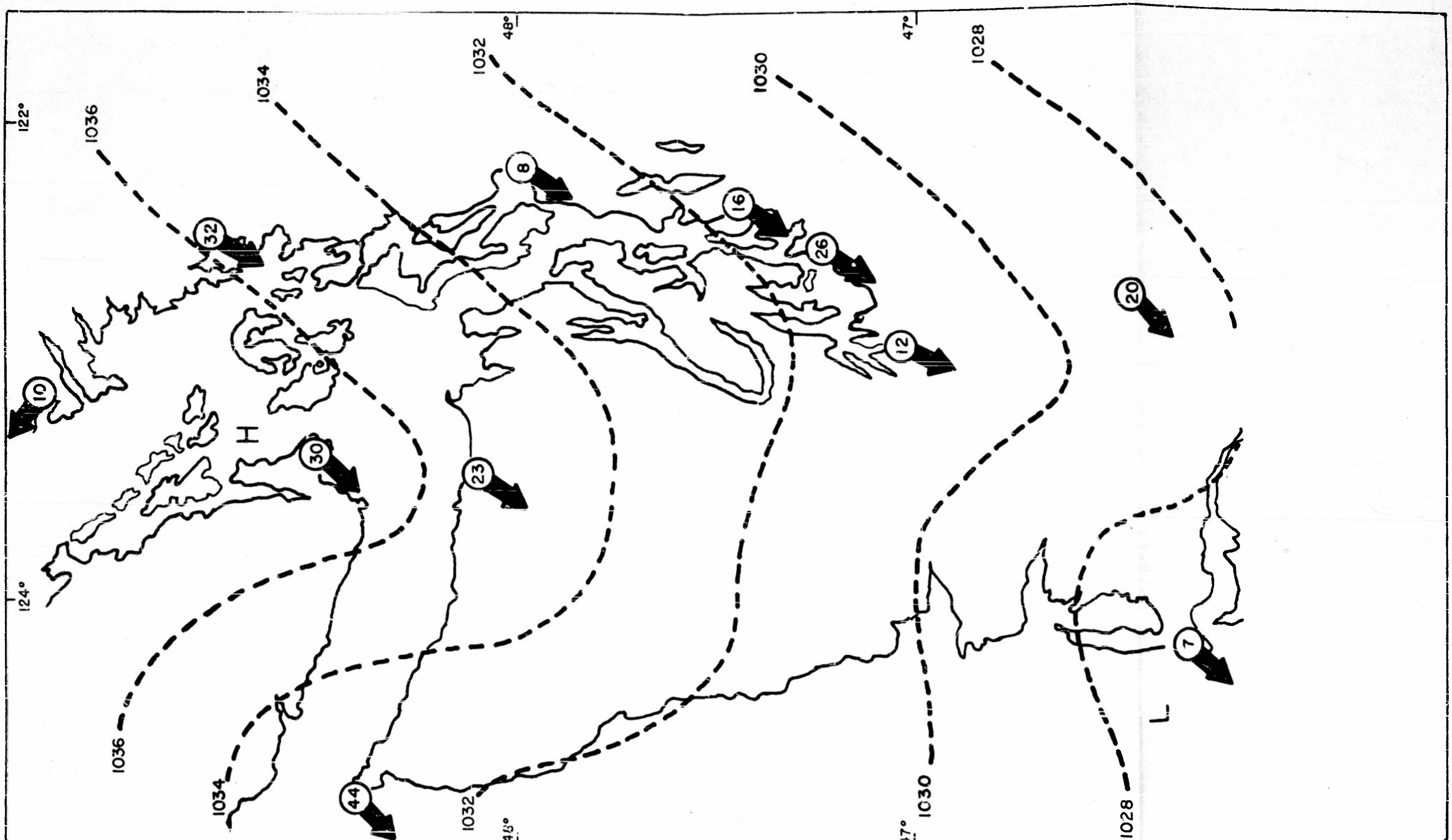

FIGURE 14. Surface wind flow 0400 PST, 28 January 1951. Dashed lines indicate barometric pressure in millibars. Arrow indicates surface wind direction. Circled number represents surface wind velocity in miles per hour.

Range and passed on down the Cowlitz Valley, with a much weaker stream moving through the Chehalis River valley. This pattern seems substantiated by the weak northeasterly flow at North Head, and the stronger winds at Toledo.

To the north, the cold flow passed to the west through the Strait of Juan de Fuca and apparently was deep enough there to cross the mountains of Vancouver Island during the 27th. This was indicated by reports at Tatoosh Island, where gale velocities were primarily from the northeast, rather than the usual easterly direction. The prevailing direction at that station for the 27th was also northeast with an average velocity of 41 mph for the day. The peak velocity recorded was 65 mph from the northeast. Temperatures there dropped to 28 degrees, 12 degrees below normal, one of the infrequent occasions when freezing temperatures are experienced at that station.

An investigation of temperature patterns occurring with polar outbreaks of this nature has been made by Stephens.[4]

April - September

Over Puget Sound the frequency of high velocities from southerly directions decreases rapidly during the spring and early summer months, reaching a minimum during July and August. During these months such winds occurred only on an average of one or two days per month.

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[4]Stephens, Thomas E.: "Temperatures in the State of Washington as Influenced by the Westward Spread of Polar Air over the Rocky and Cascade Mountain Barriers", Master of Science thesis, 1952, Library, University of Washington.

The average duration also decreases to 3 to 5 hours, but with an incongruous maximum of 8 to 13 hours at Seattle-Tacoma airport. The frequency of occurrence and duration of high winds from northerly directions however remain about the same as for the winter months.

The Port Angeles graph shows the effect of a very strong summertime diurnal variation. This effect is of such strength that surface winds over 18 mph could be expected on two days out of three during the month of July. The development of this high frequency was noticeable during the three preceding months, and during early autumn months decreased again to a minimum of 4 days per month in November.

These diurnal winds were confined sharply to the west and west-northwest directions only, and during July maintained an average duration of 11 hours. They usually reached the 18 mph level around noon and continued until near midnight.

On some occasions the high velocities continued through a 24 hour period, and in one case, July 21-23, 1950, persisted for 42 hours. These latter occasions were, surprisingly enough associated with persistent high pressure conditions and fair weather. This fact might lead one to suspect that the strength and persistence of these winds may be linked to the dynamic stability of the air masses moving eastward through the Strait of Juan de Fuca. Greater stability would, of course, be more probable under high pressure subsidence conditions, and would increase the tendency of the flow to be guided by topographical features.

The diurnal effect is present to a greater or lesser degree over almost all portions of the inland water system.

Beamer[5] has discussed in particular its pattern over the San Juan Archipelago. However, during the period under investigation here, wind velocities of the magnitude and frequency noted above were recorded only at Port Angeles. On infrequent occasions, diurnal velocities of 18-20 mph were discernible at Bellingham from the south and southsoutheast. Their duration, however, did not exceed 4 hours, and the frequency was only 3 days out of the month in July. During the periods of high diurnal winds at Port Angeles, one is probably safe in assuming that they also exist with equal strength in the portions of the Strait between Port Angeles and Tatoosh Island. The strong flow apparently decreases considerably over the eastern portions of the Strait, since the stations at Whidbey Island and Bellingham showed no comparable surface wind velocities during even the most protracted periods of strong diurnal winds at Port Angeles. The data for the two latter stations do show, however, the influence of the effect to a much lesser degree. The Bellingham graph (see Fig. 10) shows a secondary maximum of both frequency and duration in July and August. That for Whidbey Island (see Fig. 9) shows a secondary maximum at that time for duration only.

The particular case noted above, on 21-23 July 1950, (see Fig. 7), was an excellent example of this situation. During that period,

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[5]Beamer, Carol C., "The Structure of Summer Wind Over San Juan Island, Washington." Yearbook of the Association of Pacific Coast Geographers III 31, 1937.

winds at Port Angeles remained over 18 mph for 42 hours and averaged 20 to 25 mph daily. The winds remained over 15 mph for a much longer period. From 1600 hours on July 21 until 2400 hours on July 25 there were no hourly wind reports of less than 15 mph recorded at Port Angeles. All winds were from the west or westnorthwest and daily averages for all days were close to 20 mph. Furthermore, during no portion of this period were any reports of surface winds over 17 mph recorded at either Whidbey Island or Bellingham.

It cannot be determined from the present data whether, during these high winds at Port Angeles, there is any compensating flow along the coast of Vancouver Island, since there are no reporting stations there. Data from Victoria might offer some indication, but these were not readily available. Furthermore, whereas the flow past Port Angeles is completely blocked to the south, the topographical situation at Victoria permits free access from and to the north. This would probably decrease the possibility that reports from Victoria would reflect flow to the west along the northern shore of the Strait of Juan de Fuca.

If there is no such return circulation, and a net flow enters the Strait, this diurnal effect at Port Angeles could be considered as a source of the prevailing northerly winds over Puget Sound during the summer period.

October - November

During the months of October and November, the picture rapidly returns to that shown for the winter months. The frequency of high

southerly winds between the two mountain ranges increases, while the diurnal effect in the Strait of Juan de Fuca, as shown by the Port Angeles data, deteriorates rapidly until a minimum frequency of high westerly winds at that station is reached in November.

The duration of high surface winds also increases gradually everywhere over the area except in the Strait of Juan de Fuca, where it decreases slightly from that of the summertime diurnal winds.

<u>High Surface Winds Associated with Anticyclonic Meteorological Conditions</u>

The previously described cold polar outbreak from the interior was not the only occasion observed when above average surface wind velocities were associated with high pressure conditions. During accumulation of the data, it was noted that throughout all seasons of the year, periods of regional high surface winds occurred occasionally with the passage of high pressure ridges and fair weather conditions over the area, as well as with the more frequent low pressure storm centers. The flow pattern was generally northerly with the passage of these pressure maxima; usually the direction of flow changed very little, the only effect being the increased velocities immediately preceding and/or succeeding the high pressure maximum.

The data from Seattle-Tacoma airport indicate that region is especially susceptible to periods of excessive surface winds with the passage of pressure maxima. On at least a dozen occasions this station recorded extended periods of above average winds associated with clear skies and anticyclonic conditions. These were observed from March through October.

In many of these occurrences the high velocities were recorded only at this station; those at Sand Point, Everett and Tacoma showing no high winds whatever. An example of this curious situation is found during 13-14 October, 1952, when Seattle-Tacoma airport recorded northerly winds between 18 and 25 mph for 22 hours. Tacoma, Sand Point NAS and Everett recorded no winds over 18 mph. Again, on 10-11 April, 1951, Seattle-Tacoma airport recorded northerly winds between 18 and 25 mph for 30 hours; Tacoma recorded them for 3 hours only and Everett and Sand Point NAS recorded none over 18 mph. The wind flow and isobaric configuration at 0400 PST on April 11, 1951 is shown in Fig. 15. Both of these occasions were associated with high pressure maxima.

The reason for this effect, and also the fact that throughout the year high surface winds are generally of greater duration at Seattle-Tacoma airport than at other stations in the vicinity cannot be satisfactorily explained. Although one would be inclined to suggest the immediate topography as a cause, a study of the detailed relief of the area does not reveal any obvious topographical features which would cause a funneling or Venturi effect of the necessary magnitude in that immediate region.

Nor can it be explained by the elevation of the station at Seattle-Tacoma airport, which is 388 feet above mean sea level. The station at Sand Point is at 54 feet, and may be protected from southwesterly flow reaching the Sound, but the station at Everett is at 598 feet, while Tacoma is at 165 feet. Both of these latter stations would, therefore, have approximately the same exposure to general flow

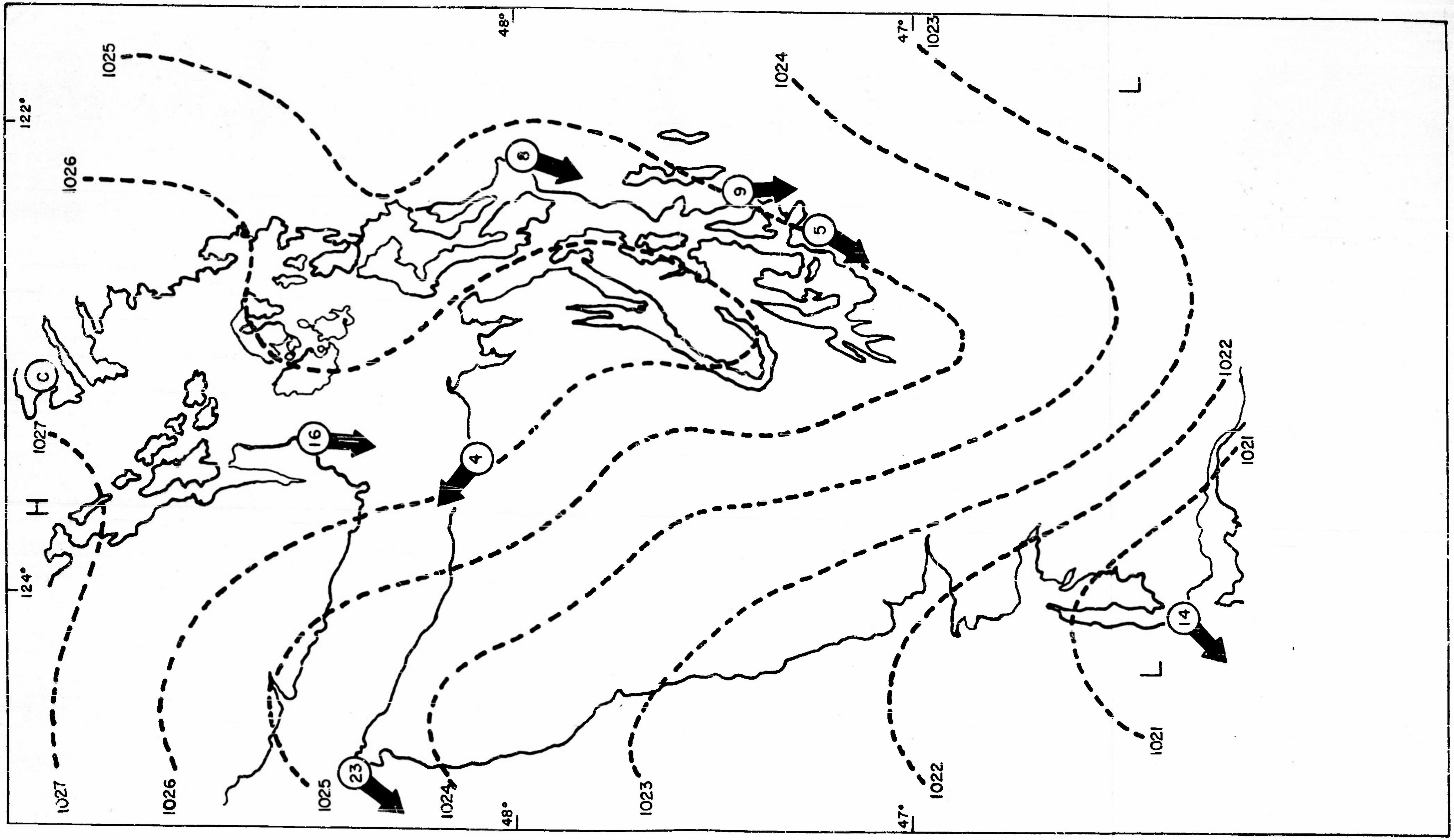

FIGURE 15. Surface wind flow 0400 PST, 11 April 1951. Dashed lines indicate barometric pressure in millibars. Arrow indicates direction of surface wind. Circled number represents surface wind velocity in miles per hour.

as that at Seattle-Tacoma airport,

If it were to be explained on a larger scale as the result of convergence of air streams flowing eastward through the Chehalis River valley and northward through the Cowlitz Valley one would have to explain why the station at Tacoma should not show similar effects.

CHAPTER IV

AN ESTIMATION OF MAXIMUM SURFACE WIND WAVES ON INLAND WATERS DURING 1950 - 1952

An attempt was made to estimate the maximum height of the wind waves which were formed over Puget Sound during the period for which the accumulated high surface wind data were representative. For this purpose, use was made of the methods devised by H. U. Sverdrup and W. H. Munk shortly after World War II, and described in detail in Navy H. O. Publication No. 604.[6]

As described in this publication, wind waves are limited primarily by two factors; the duration of the time during which the wind blows over the water surface, and the "fetch", or length of continuous water surface over which the wind may blow.

Puget Sound

Over much of Puget Sound, fetches are sufficiently short to be the restricting factor in the formation of wind waves. Fig. 16 shows the particular fetches of 15 miles or over which would permit waves of 8 feet in height to be generated. The longest of these is 34 miles, extending from Point Robinson on Maury Island to Useless Bay, on the southern end of Whidbey Island.

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[6] United States Navy Hydrographic Office, "Techniques for Forecasting Wind Waves and Swell", H. O. Publication No. 604, Washington, D.C., 1951.

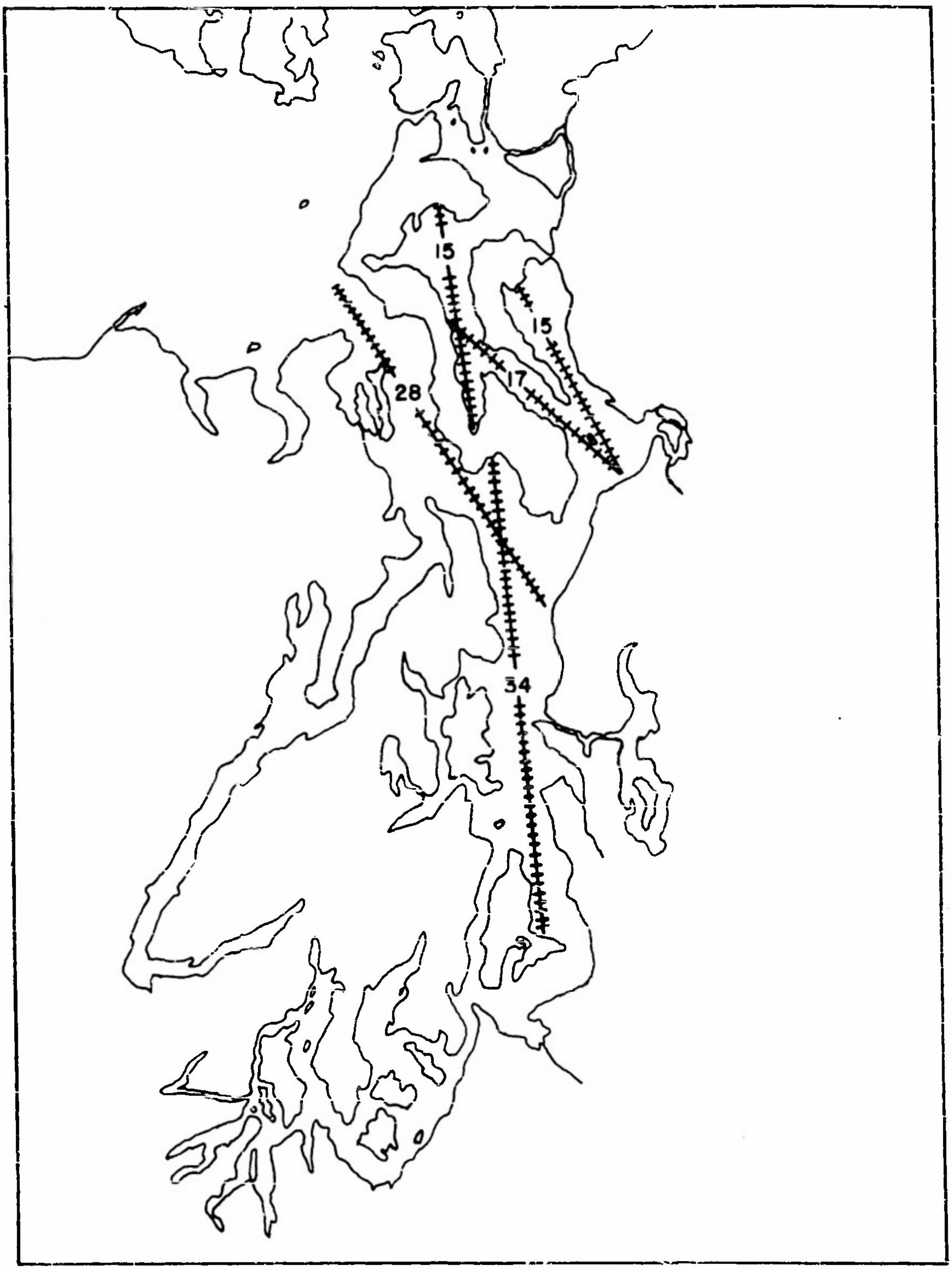

FIGURE 16. Fetch lengths on Puget Sound system (in nautical miles).

Fig. 17 is a graph derived from those in the above-mentioned publication which indicates the height of waves to be expected from above average wind velocities of varying duration periods. The dashed lines indicate the limiting restrictions of various fetch lengths. These determine the maximum height the wind waves will attain for a given wind velocity regardless of the actual duration of the wind.

The estimation of wind wave heights was made for the longest fetch shown, of 34 miles. In view of the orientation of this particular fetch, the winds considered were restricted to those from directions between southsoutheast and southsouthwest, and between northnorthwest and northnortheast. In addition, the simultaneous observations from stations at Tacoma, Seattle-Tacoma airport, Everett and Whidbey Island were examined and correlated to determine the maximum duration of the wind over the given fetch.

Averages were taken between velocities shown at the stations near the upper and lower ends of the fetch to obtain the most representative value for the entire length of the fetch. It was found possible to confine the duration of the winds to the period when stations representing both ends of the fetch were recording high wind velocities from the appropriate directions. In nearly all cases, these periods were sufficient for the average velocities obtained to permit maximum wave development over the fetch.

The results of these calculations are listed in Table 4, and show that over the three year period waves of 6 feet in height or greater were indicated on 17 different occasions. In the case of winds from the southerly direction segment, waves of over 6 foot heights were

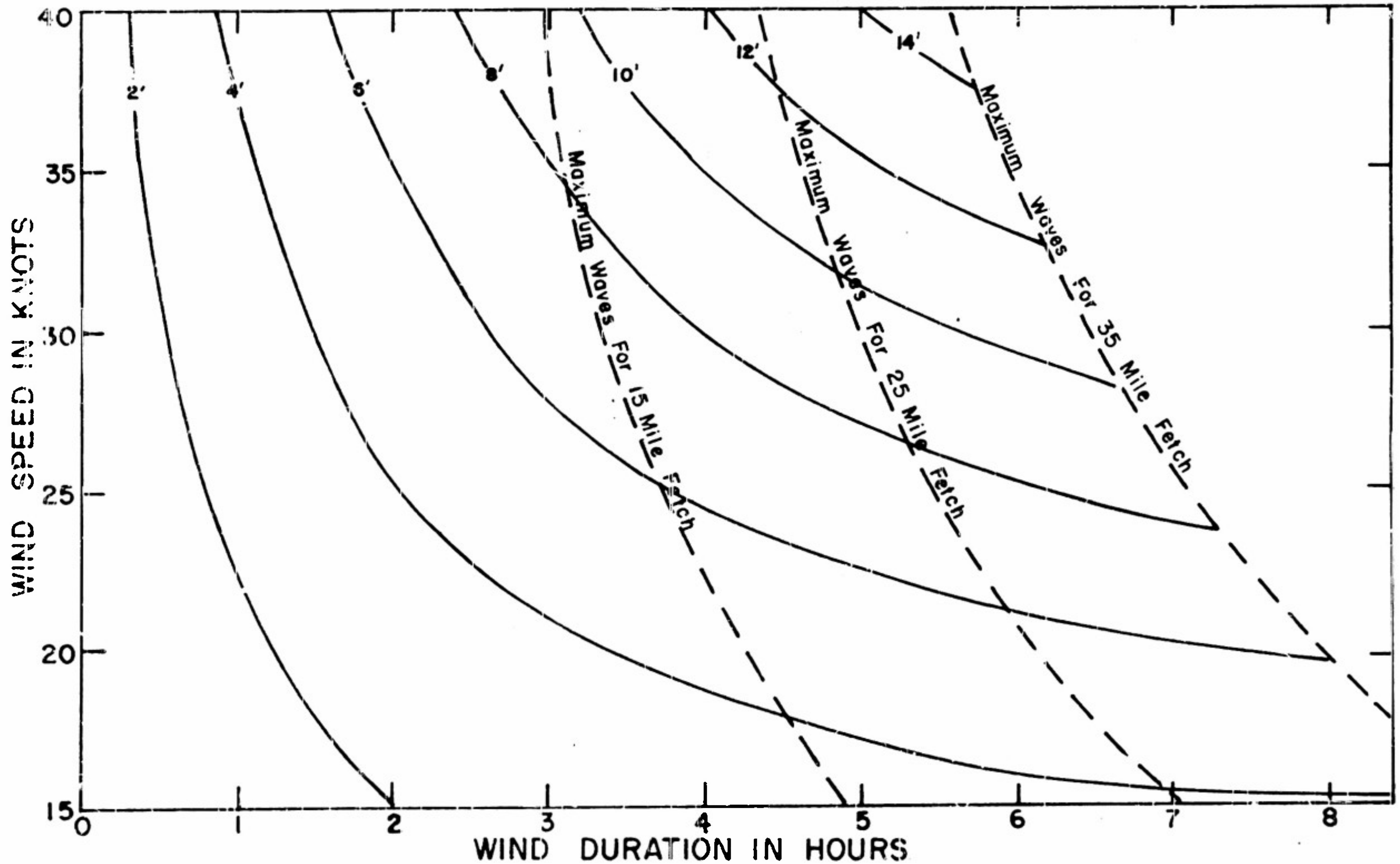

FIGURE 17. Wind wave height as a function of wind speed, duration of wind and length of fetch. Solid lines represent wave height in feet.

TABLE 4

MAXIMUM WIND WAVES ON PUGET SOUND
FOR PERIOD OF JANUARY 1950 TO DECEMBER 1952

Year	Date	Wind Direction	Average Velocity (mph)	Duration (hrs)	Wave Height (ft)
1950	Jan 2	NNE-NNW	25	8	8
	Jan 10	SSE-SSW	27	7	8
	Jan 13	NNE-NNW	26	6	8
	Jan 24	NNE-NNW	22	8	6
	Feb 8	SSE-SSW	23	8	7
	Feb 25	SSE-SSW	25	6	8
	Mar 3	SSE-SSW	23	8	7
1951	Jan 13	SSE-SSW	22	8	6
	Jan 24	SSE-SSW	23	8	7
	Jan 27	NNE-NNW	24	8	8
	Mar 5	SSE-SSW	20	8	6
	Dec 29	SSE-SSW	25	8	8
	Dec 30	NNE-NNW	19	8	6
1952	Jan 9	SSE-SSW	24	7	8
	Nov 14	SSE-SSW	26	8	9
	Dec 3	SSE-SSW	20	8	6
	Dec 7	SSE-SSW	24	8	6

possible on 12 occasions during the months of November through March, and the maximum value obtained was 9 feet on 14 November, 1952. For the winds from the northerly quadrant, heights of 6 feet and above were obtained on 5 occasions during the months of December and January only, with a maximum value of 8 feet. The occasions associated with southerly winds were more regular in occurrence, 4 times per year. Those associated with northerly winds were found 3 times in 1950, twice in 1951 and none at all in 1952.

It is perhaps worthy of note here that the more realistic wind speed and duration values obtained by averaging reports from the opposite ends of the fetch result in much lower values than would be obtained if the reports for Seattle alone were used. The exclusion of the direction of southwest also results in lower height values. The highest durations and velocities of southerly winds were noted at Seattle-Tacoma airport from the southwest. The extreme example occurred on January 15, 1951, when the wind velocity averaged 35 mph for a period of 7 hours, the direction varying from southsouthwest to southwest.

If one were to use this velocity as representing the wind over the entire fetch, and further assume that the wind was sufficiently "funneled" by the topography to flow uninterrupted over the entire length of the fetch, a maximum wave height of 13 feet would be obtained. Similarly, northeast winds with average velocity of 35 mph occurred at Tacoma for a period of 6 hours. Similar assumptions as before would again permit values of 13 feet to be obtained.

It seems likely, however, that the values obtained by considering averages between two or more stations are more closely representative of the waves that would be found on Puget Sound.

It must be remembered, also, that in using for our purposes the method of computation as derived by Sverdrup and Munk the assumption is made that a constant wind of the average velocity suddenly begins to blow over an undisturbed water surface. Thus the values obtained do not account for waves that may already be present on the Sound at the onset of the winds considered.

The Strait of Juan de Fuca

Wind wave height estimates for the Strait of Juan de Fuca will probably be more subject to error due to waves which exist prior to the duration time considered. This would be expected since these waters, in contrast to those of Puget Sound, are open to waves and swell from the open sea. This type of error would be more likely to be present during the winter months, when frequent offshore storms cause heavy swell and waves to enter the Strait. Nevertheless, estimates were made for maximum wind waves created on Strait waters during the period considered, as a rough means of comparison with those on Puget Sound.

In January, two occasions were chosen which showed optimum conditions for wind wave creation by winds from westerly and northeasterly directions.

During the storm of January 2, 1951 previously discussed, maximum waves could be estimated for an 8 hour period during which wind velocities at Port Angeles averaged 30 knots from westerly directions.

From these conditions wind wave height values of 13 feet were calculated. In obtaining this maximum value, the velocities considered were the determining factor, since the fetch length along the Strait, over 60 nautical miles, was more than sufficient for maximum wave development by the recorded winds.

For winds from an eastnortheasterly direction, optimum conditions were found on 13 January, 1950. These winds occurred during a polar outbreak similar to that previously discussed for January 26-28, 1951. In the case of 13 January, 1950, however, the strong easterly and northerly winds resulted from an intense low off the Washington coast which furnished sufficient pressure gradient to bring the cold air from the interior onto the Puget Sound Basin. The winds appeared at Bellingham from the northnortheast to northeast, and at Port Angeles from the northeast to eastnortheast. Therefore an appropriate fetch was indicated as extending from the San Juan Islands southwestward to the Olympic mountains west of Port Angeles, a distance of about 30 nautical miles. Maximum wave heights were obtained during a 4 hour period on January 13, 1950. Consideration of a longer period was unnecessary because of the short fetch length. During this period winds at Bellingham averaged 55 mph from the northnortheast to northeast, while those at Port Angeles were 44 mph from the eastnortheast to northeast. An average of the values at these two stations results in a calculated wave height of 15 feet.

Both of the storms discussed above were characterized by intense low pressure centers offshore. Therefore, waves and swell created in the southeastern quadrant of these centers had in all probability

entered the Strait and were present at the onset of the high winds in the Strait itself. Consequently, the westerly winds of January 2, 1951 would be reinforcing the waves and swell already present, while the northeasteriies on January 13, 1950 would act toward deteriorating them.

During the summer months, the presence of the exceptionally strong diurnal flow in the western portions of the Strait can very possibly lead to almost daily occurrence of wind waves of considerable height. Consequently, calculations were made toward estimating the wave heights to be expected.

Optimum conditions were found to exist on July 31, 1952, when wind velocities recorded at Port Angeles averaged 30 mph from westerly directions for an 8 hour period. For this period calculated wave heights were 9 feet. Since the high velocity diurnal winds had been found to occur on an average of two days out of three during the summer months, a second calculation was made to determine the average wave height to be expected on those days. An examination of the duration data yielded an average daily velocity of 22 mph for these diurnal winds and this value, along with the average duration of 11 hours previously obtained, leads to an expected wave height of 7 feet.

These wave height values obtained from the summer time winds at Port Angeles are in all probability much more representative of conditions actually observed on the surface of the Strait than those obtained for the winter months. This seems likely in view of the fact that the flat pressure gradient associated with the predominant high pressure area offshore during the summer period would in general preclude the formation of heavy swell or high wind waves which would enter

the Strait. It also would furnish a long region for "decay" of waves or swell formed further westward in the Pacific. Under these circumstances waves observed in the Strait would be almost entirely due to the wind stress occurring within the confines of that water body itself.

CHAPTER V

WIND STRESS ON PUGET SOUND

In addition to the heights of wind waves it is desirable, from an oceanographic viewpoint, to determine, insofar as possible, the magnitude of the stress exerted by the wind upon the water surface, and the currents and water level slopes which may result from such stress. Consequently, the wind data compiled for this report have been examined for the purpose of obtaining a semi-quantitative picture of the wind stress which may be exerted on Puget Sound waters at different times of the year.

Various investigators (Ekman, von Karman, Wust, et al) have considered the problem of frictional stresses at fluid boundary surfaces and have derived empirical relationships between wind velocity and the stress exerted by such wind on the surface of a water body. Other expressions have been found to show relationships between this stress and the resultant currents and water level slopes. The reader is referred to the comprehensive discussion of these formulae given by Sverdrup, Johnson and Fleming.[7]

The calculations of the wind stress over Puget Sound made in this report have been divided into two categories; that resulting from winds flowing over the Sound from northerly directions (NE-NW), and that from southerly directions (SE-SW). Division of the data in this manner was

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[7]Sverdrup, Johnson and Fleming, "The Oceans", (New York, Prentice Hall, 1949, p. 471-503.

considered desirable from the standpoint of its later oceanographic use because of the longitudinal north-south configuration of the Sound, and the fact that the prevailing wind flow at nearly all times of the year is oriented along its length from either a northerly or southerly direction.

The wind data from these stations, Everett, Seattle-Tacoma Airport and Tacoma were used in the calculations. The frequency, in percentage of the total observations taken, and the average velocity for the given directional ranges were determined for each month. This velocity was then used to obtain an estimation of the average wind stress which might be expected as a result of the winds flowing over the Sound from each of the two direction quadrants.

The calculations were made from the expression

$$T_a = 0.0026\rho' W^2$$

where T_a equals the wind stress in dynes/cm^2, ρ' represents the air density in gm/cm^3 and W equals the wind velocity in cm/sec at an elevation of 15 meters above the water surface. This expression incorporates the findings of Rossby, Ekman and others[8] with respect to wind stress and velocity for moderate wind speeds.

A pertinent source of error is, of course, evident as a result of the varied elevations of the stations considered. The formula is based upon the wind velocity at 15 meters above the water surface. However, our calculations are made on the assumption that this wind is represented by the recording instruments at each station. However,

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[8] _Op. Cit._, p. 490

it was felt that an attempted correction for this error, obtained by assuming a standard wind profile, would contribute little to the accuracy of the results, in view of the averaging processes used, and the lack of information regarding the stability conditions which prevail at each station.

Rossby has indicated that at low wind velocities a different expression based upon the existence of laminar air flow near the surface of the water should be used, and that stress magnitudes thus obtained would be approximately one third those obtained from the above formula. Munk[9] arrived at the same conclusion, and states that at wind velocities below 6.6 meters per second (14.5 mph) the above equation should be replaced by

$$T_a = 0.0008\,\rho''W^2$$

It is noted, however, that in either expression the stress is proportional to the square of the wind velocity. The present calculations, then, are based upon an expression for wind flow with velocities greater than 6.6 meters per second.

Fleming, et al,[10] have shown that at wind velocities below this value the resultant wind stress would be almost negligible. It would be desirable, therefore, to exclude wind velocities below that level in

[9] Munk, Walter H., "A Critical Wind Speed for Air-Sea Boundary Processes", Journal of Marine Research 6 (1947), p. 205-218.

[10] Sverdrup, Johnson and Fleming, op.cit., p. 491.

obtaining our average velocities. Unfortunately, however, no summaries were available from which such an elimination would be possible.

The use in the equation of average, rather than instantaneous, wind velocities creates a further source of possible error. Since the stress is proportional to the square of the wind velocity, a greater relative contribution to the stress value calculated would be made by the higher wind velocities. Thus an average wind velocity considered constant over all observations might yield calculated stress values at variance with those obtained by a summation of the contributions made within the individual velocity ranges. A correction factor was sought to compensate for this misrepresentation. Available for the purpose was a tabulation of the annual frequency and velocity distribution of wind observations at Seattle-Tacoma Airport, which listed average wind velocities and frequency of occurrence of winds from all directions, within each Beaufort velocity range.

From this information the value of the square of the wind velocity over the total period could be determined in two ways; by use of the square of the average velocity over 100 percent of the period, and by a summation of the products of the squares of the individual velocity ranges and their corresponding frequencies. A comparison of the two results yielded a correction factor, to be applied to the value obtained from the average wind velocity. Since the annual tabulation was available for Seattle-Tacoma Airport only, it was necessary to use the factor obtained for this one station as representative of the entire Sound. The derivation of this factor is shown in Table 5, and indicates that stress values derived from the average wind velocity

would be, in general, less than those derived from a summation of stresses resulting from the individual velocity ranges by a factor of 1.6. Incorporating this factor, and assuming air density equal to 0.00125 gm/cm^3, our equation becomes

$$T_a = 5.1 \times 10^{-6} \bar{W}^2$$

where $\bar{W}$ represents the average wind velocity.

Using this formula, values have been determined which represent the average wind stress over Puget Sound for each month, from both southerly and northerly wind flow. The values for each of the three given stations, and the combined average are given in Tables 6 through 9. Percentages representing the relationship of flow from each direction quadrant to the total number of observations for the period are also listed to give an approximation of the frequency of occurrence of winds from each of the two directions during each month.

It is again emphasized that, in view of the averaging processes used, and assumptions made in the choice of the original equation, the values are probably accurate only in degree of magnitude. However, their relationships would seem to give a fair picture of the seasonal ebb and flow of wind stress over the Sound from the two direction quadrants.

The dominant feature of the values obtained is the inverse seasonal variation between stresses exerted by winds from the two directions. The average stress resulting from northerly winds rises gradually to a maximum of 0.96 dynes/cm^2 in July, with a minimum of 0.59 dynes/cm^2 in December. That resulting from winds from the southern

TABLE 5

DERIVATION OF CORRECTION FACTOR FROM

ANNUAL WIND FREQUENCY AND VELOCITY DISTRIBUTION AT

SEATTLE - TACOMA AIRPORT

A Percentage of Total Obsvtns.	B Mean vel. (mph)	C (Mean vel.)^2	A x C
19.0	2	4	76
17.0	6	36	102
32.0	10	100	3200
22.0	16	256	5632
7.5	22	484	3630
2.0	28	784	1568
0.5	35	1225	612
0.03	43	1764	53

Sum - (mean velocity)^2 x % = 14773

Average annual velocity = 9.8 mph

(Average annual velocity)^2 x 100% = 9604

Correction Factor = $\frac{14773}{9604}$ = 1.6

TABLE 6

MONTHLY WIND FREQUENCY AND VELOCITY AND WIND STRESS T_a

EVERITT, WASHINGTON

MONTH	NORTHERLY WINDS (NE - NW) FREQUENCY (%)	VELOCITY (cm/sec)	STRESS T_a (dynes/cm^2)	SOUTHERLY WINDS (SE - SW) FREQUENCY (%)	VELOCITY (cm/sec)	STRESS T_a (dynes/cm^2)
JAN	20	326	0.54	54	425	0.92
FEB	24	322	0.53	52	447	1.01
MAR	26	362	0.67	51	456	1.03
APR	36	353	0.64	42	420	0.90
MAY	45	376	0.72	34	411	0.86
JUN	52	389	0.77	26	344	0.60
JUL	54	384	0.75	23	367	0.69
AUG	5[illegible]	366	0.69	28	335	0.57
SEP	51	344	0.60	29	376	0.72
OCT	35	326	0.54	42	371	0.70
NOV	21	300	0.46	55	425	0.92
DEC	20	291	0.43	56	447	1.01

TABLE 7

MONTHLY WIND FREQUENCY AND VELOCITY AND WIND STRESS T_a

SEATTLE - TACOMA AIRPORT, WASHINGTON

MONTH	NORTHERLY WINDS (NE - NW) FREQUENCY (%)	VELOCITY (cm/sec)	STRESS T_a (dynes/cm^2)	SOUTHERLY WINDS (SE - SW) FREQUENCY (%)	VELOCITY (cm/sec)	STRESS T_a (dynes/cm^2)
JAN	8	406	0.84	63	686	2.40
FEB	19	442	0.99	44	570	1.66
MAR	13	522	1.39	54	615	1.93
APR	32	526	1.41	29	540	1.49
MAY	32	508	1.33	33	540	1.49
JUN	26	508	1.33	34	500	1.24
JUL	37	548	1.53	24	424	0.88
AUG	28	463	1.09	31	442	1.00
SEP	38	531	1.47	32	464	1.10
OCT	28	503	1.29	41	495	1.25
NOV	17	411	0.86	48	482	1.19
DEC	12	397	0.80	62	566	1.64

TABLE 8

MONTHLY WIND FREQUENCY AND VELOCITY AND WIND STRESS T_a

TACOMA, WASHINGTON

MONTH	NORTHERLY WINDS (NE - NW) FREQUENCY (%)	VELOCITY (cm/sec)	STRESS T_a (dynes/cm^2)	SOUTHERLY WINDS (SW - SE) FREQUENCY (%)	VELOCITY (cm/sec)	STRESS T_a (dynes/cm^2)
JAN	15	312	0.50	46	366	0.68
FEB	18	326	0.54	44	362	0.67
MAR	15	321	0.53	45	402	0.82
APR	19	317	0.51	38	380	0.74
MAY	24	352	0.63	34	355	0.64
JUN	21	326	0.54	33	317	0.51
JUL	26	339	0.59	23	304	0.47
AUG	26	335	0.57	24	290	0.43
SEP	24	312	0.50	26	321	0.53
OCT	18	263	0.35	36	339	0.59
NOV	13	263	0.35	42	379	0.73
DEC	11	290	0.43	47	384	0.75

TABLE 9

AVERAGE MONTHLY WIND FREQUENCY AND VELOCITY AND WIND STRESS T_a

MONTH	NORTHERLY WINDS (NW - NE) FREQUENCY (%)	VELOCITY (cm/sec)	STRESS T_a (dynes/cm^2)	SOUTHERLY WINDS (SE - SW) FREQUENCY (%)	VELOCITY (cm/sec)	STRESS T_a (dynes/cm^2)
JAN	14	348	0.63	54	492	1.33
FEB	20	363	0.69	47	461	1.11
MAR	18	402	0.86	50	491	1.26
APR	29	399	0.85	36	447	1.04
MAY	34	412	0.89	34	435	1.00
JUN	33	408	0.88	31	387	0.78
JUL	39	424	0.96	23	365	0.68
AUG	35	389	0.78	28	356	0.67
SEP	38	396	0.86	29	387	0.78
OCT	27	364	0.73	40	402	0.85
NOV	17	325	0.56	48	429	0.95
DEC	14	293	0.55	55	466	1.13

quadrant is at a minimum of 0.67 dynes/cm^2 in August and at a maximum of 1.33 dynes/cm^2 in January.

The results also show that for winds from both quadrants the average stress varies directly with the frequency of the winds. The wintertime picture, with maximum wind velocity, frequency and stress magnitude associated with southerly winds, would be as expected, in view of the greater frequency of storm passages during that season of the year. Ordinarily, however, one would expect the maximum velocities and stress magnitudes from northerly winds to occur also during this period of most frequent storm passage, irrespective of the fact that their frequency is at a minimum at this time. The facts that they occur instead during the summer months, and at this time exceed in all three respects the winds from the southerly quadrant, point out even more sharply the dominance of the previously discussed prevailing northerly surface wind flow which intrudes over the Sound Basin during the summer months.

The relation between surface current and wind velocity is not known for stratified, laterally confined waters. Experience indicates that a ratio of surface current to wind velocity should be the order of five per-cent and this value will be used here to estimate current values from the measured wind velocities.

Use of the average wind velocities in Table 9 leads to current contributions from northerly winds ranging from 0.3 knots in winter months to 0.4 knots in the summer-time. For southerly winds the values vary from 0.4 knots in summer to 0.5 knots in winter months. From these results, one might conclude that on an average the Puget Sound surface waters are subject to wind currents of approximately 0.4 knots at all seasons of the year. This value may, of course, vary considerably, especially in the case of persistent high surface winds. As an example, during the storm of January 10, 1950, winds from southerly directions averaged 27 mph, and persisted for 7 hours. Use of this velocity in the above formula would yield an approximate current value of 1 knot.

A maximum current value of 1 knot can also be obtained from consideration of the northerly winds over the Sound associated with the storm passage of 13 January 1950, when the wind averaged 26 mph and persisted for 6 hours.

The values obtained above from average wind velocities would seem to indicate that during all seasons of the year currents in the surface waters of Puget Sound which are induced by wind stress are by no means negligible in comparison with the tidal currents. These latter currents [12] vary in general over the main Puget Sound Basin from 0.1 to 1.5 knots at maximum ebb and flood, although they become,

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[12] U.S. Department Of Commerce, "Tidal Current Charts, Puget Sound" Coast and Geodetic Survey, 1947.

of course, much stronger over Admiralty Inlet and in other restricted channels. Therefore, during the time that southerly or northerly surface winds are present over the Sound--approximately 65 to 70 per cent of the total period--the tidal currents might be expected to be appreciably affected by the wind stress on the water surface.

Computations may also be made using the average stress values of Table 9 to obtain an estimate of at least the order of magnitude of the portion of the total water level slope which is due to wind stress on the water surface. The expression used for this calculation is

$$T_a = - g\, d\, i\, h\ ,$$

where (in cgs. units) T_a again represents the stress of the wind, g is the acceleration of gravity, d the density of the water, i the slope of the water surface and h is the depth of the water. This formula has been obtained[13] by integration of the equations of motion, assuming homogeneous water, stationary conditions and a rectangular configuration of the water body.

Using gd equal to 1000, and an average depth of the Sound Basin of 64 meters, the equation becomes

$$i = 0.02\ T_a \text{ cm/Km}$$

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[13]Sverdrup, Johnson and Fleming, op.cit., p. 488

Use in this formula of the maximum and minimum stress values listed in Table 9 would indicate that the average slope due to wind stress over the Sound varies from 0.01 to 0.03 cm/Km, which, if a value of 100 Km is further assumed to represent the north-south length of the Sound, will yield variations of 1 to 3 centimeters in elevation of the water level surface over the length of the Sound.

A calculation was also made to obtain an estimation of the slope which might have occurred during the storm of January 10, 1950, when the average wind velocity of 27 mph was recorded. From this velocity a stress estimation of 4.68 dynes/cm^2 was obtained, which when substituted in the above equation yields a slope estimation of 0.09 cm/Km, or a difference in water level over the Sound of 9 cms.

A possible check on this latter value may be obtained by using in lieu of the above equation a similar one derived empirically by Colding[14], i.e.

$$i = \frac{4.8 \times 10^{-9} W^2}{h}$$

where W again represents the wind speed in cms/sec. Use of this equation with the 27 mph wind velocity and the average depth of 64 meters yields a slope value of 0.11 cm/Km, and a resultant water level slope over the Sound of 11 cms.

It is noted here that the estimations made for the average depth and length of the Sound might be separately or simultaneously varied

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[14]Colding, op.cit., p.490

over a wide range of possible values without changing to any appreciable extent the magnitude of the slope over the Sound.

The calculations from the two equations seem to indicate that water level slopes which occur over the Sound as a result of wind stress are, in contrast to the currents induced, relatively negligible with respect to tidal effects.

A record is available, however,[15] which indicates an increase of 2 feet above the predicted high tide level at Seattle that was considered due to the combined barometric pressure and wind stress effects resulting from a storm off the mouth of the Strait of Juan de Fuca during this period.

If the slopes due to wind stress are of the small magnitude indicated above, then this fact would seem to justify a conclusion that non-tidal water level slopes of any appreciable magnitude which might occur over the Sound would be due primarily to barometric pressure differences, with negligible contributions from wind stress over the Sound. This conclusion would indicate, then, that an investigation of simultaneous meteorological and water level records might be fruitful in determining a usable empirical relationship between water level heights, wind stress and barometric pressure gradients over the Sound.

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[15] Department of Oceanography, University of Washington, "Oceanographic Survey on Submarine Portion of Snohomish-Kitsap 230 KV Line. Final Report. Part I." University of Washington, Seattle, Washington.

CHAPTER VI

SUMMARY

An analysis of accumulated wind rose summaries shows the prevailing flow over Puget Sound to be southerly in the winter-time. During the summer months prevailing northerly flow intrudes southward over the Sound from the Admiralty Inlet area, reaching the Tacoma-Olympia vicinity by September. In autumn this northerly flow deteriorates more rapidly than it developed, and prevailing flow is again found to be southerly in October.

In the Strait of Juan de Fuca, the prevailing flow is easterly in winter, and westerly in the summertime. The possibility of a frequent closed circulation over the eastern end of the Strait of Juan de Fuca and southern portions of Georgia Strait is suggested. Examples are given to indicate that the prevailing flow pattern may frequently exist simultaneously over the area.

Data were obtained which show the frequency and duration of all surface winds of velocity 18 mph or greater. These indicate that the direction of strong surface flow is sharply confined by the topographical configuration of the area.

It is pointed out that these winds occur not only with the passage of pressure minima, but also on frequent occasions with the occurrence of high pressure maxima. The station at Seattle-Tacoma airport is especially susceptible to this latter feature, but the immediate topography of that area offers no obvious clue as to its cause.

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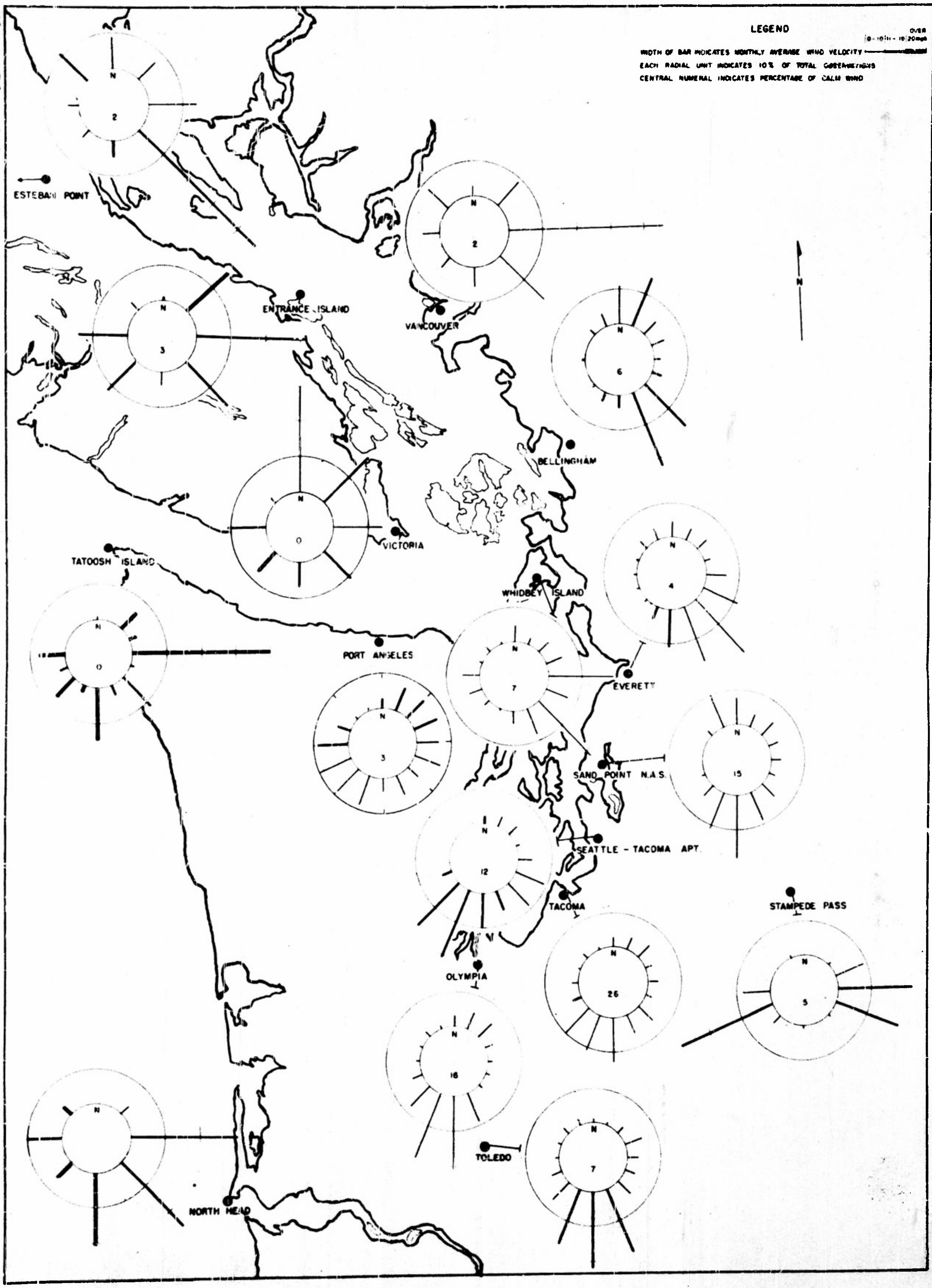

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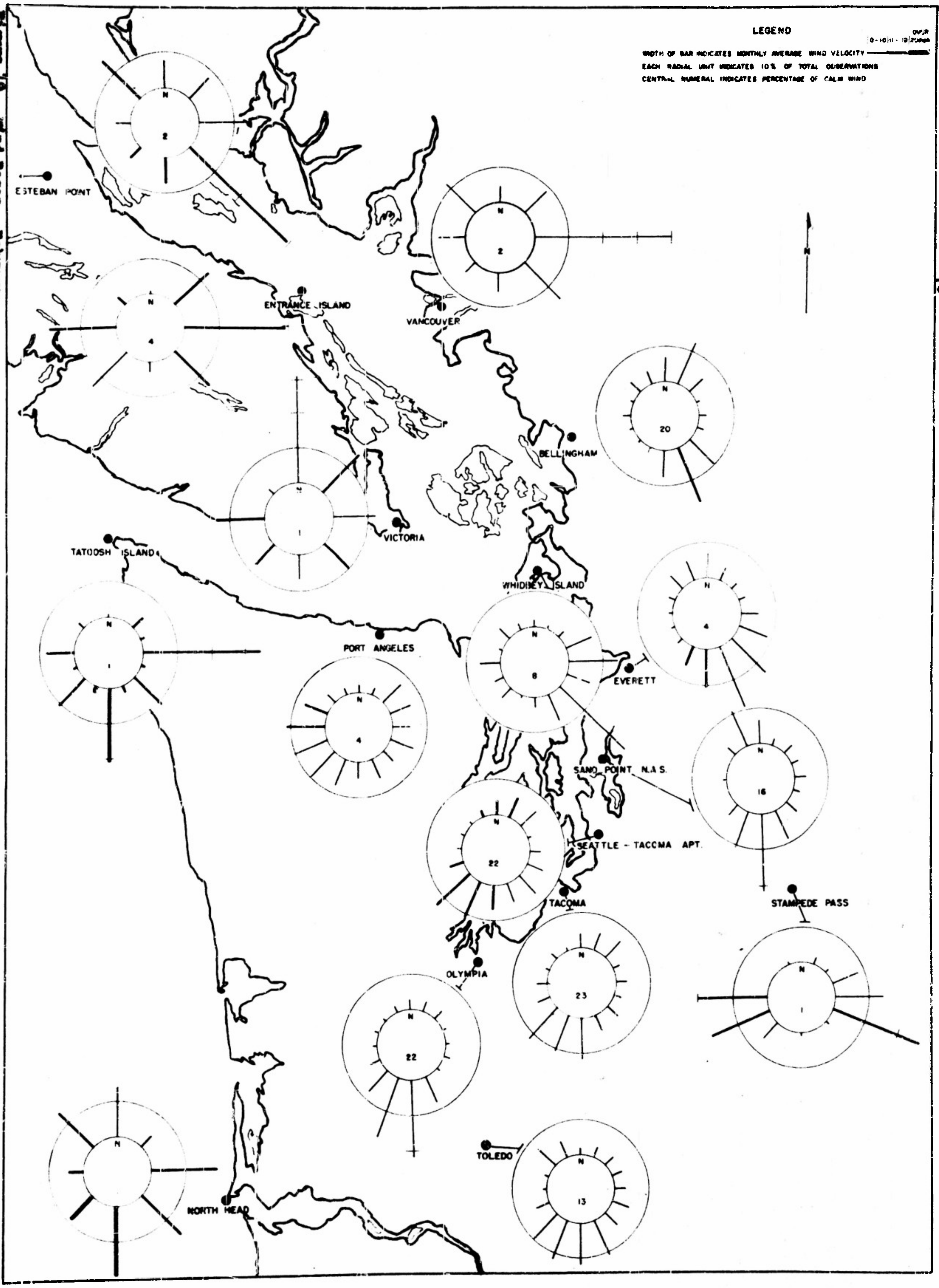

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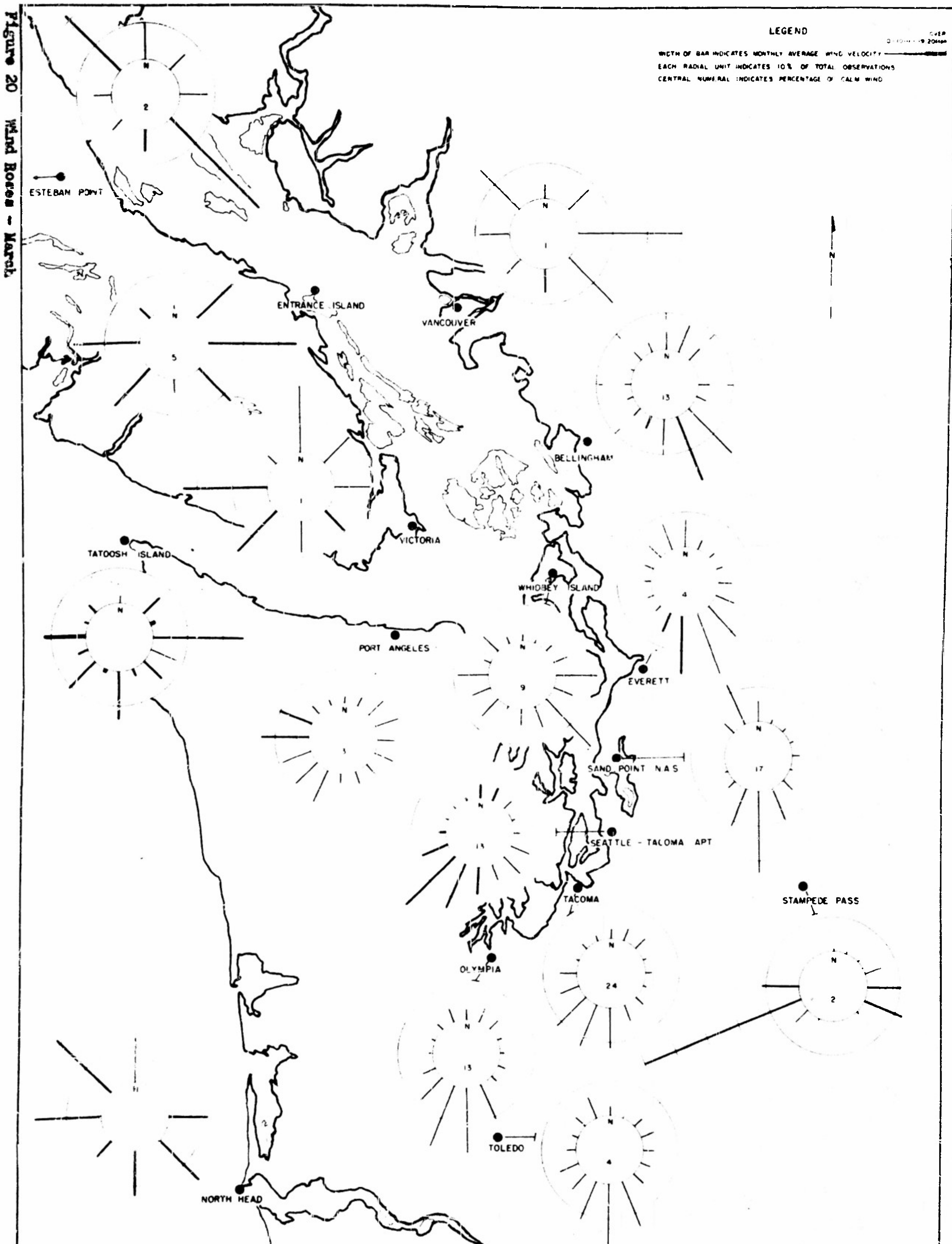

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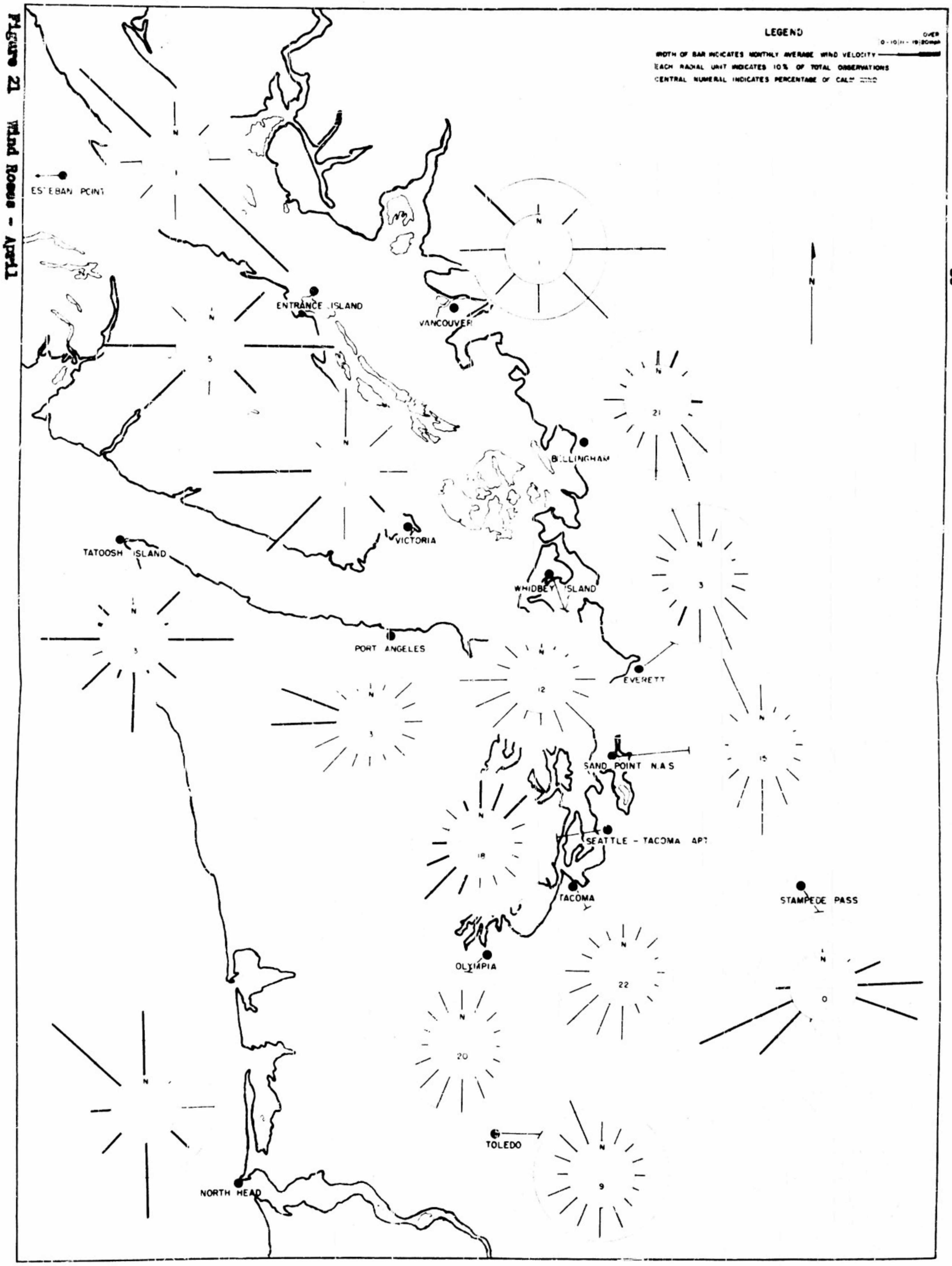

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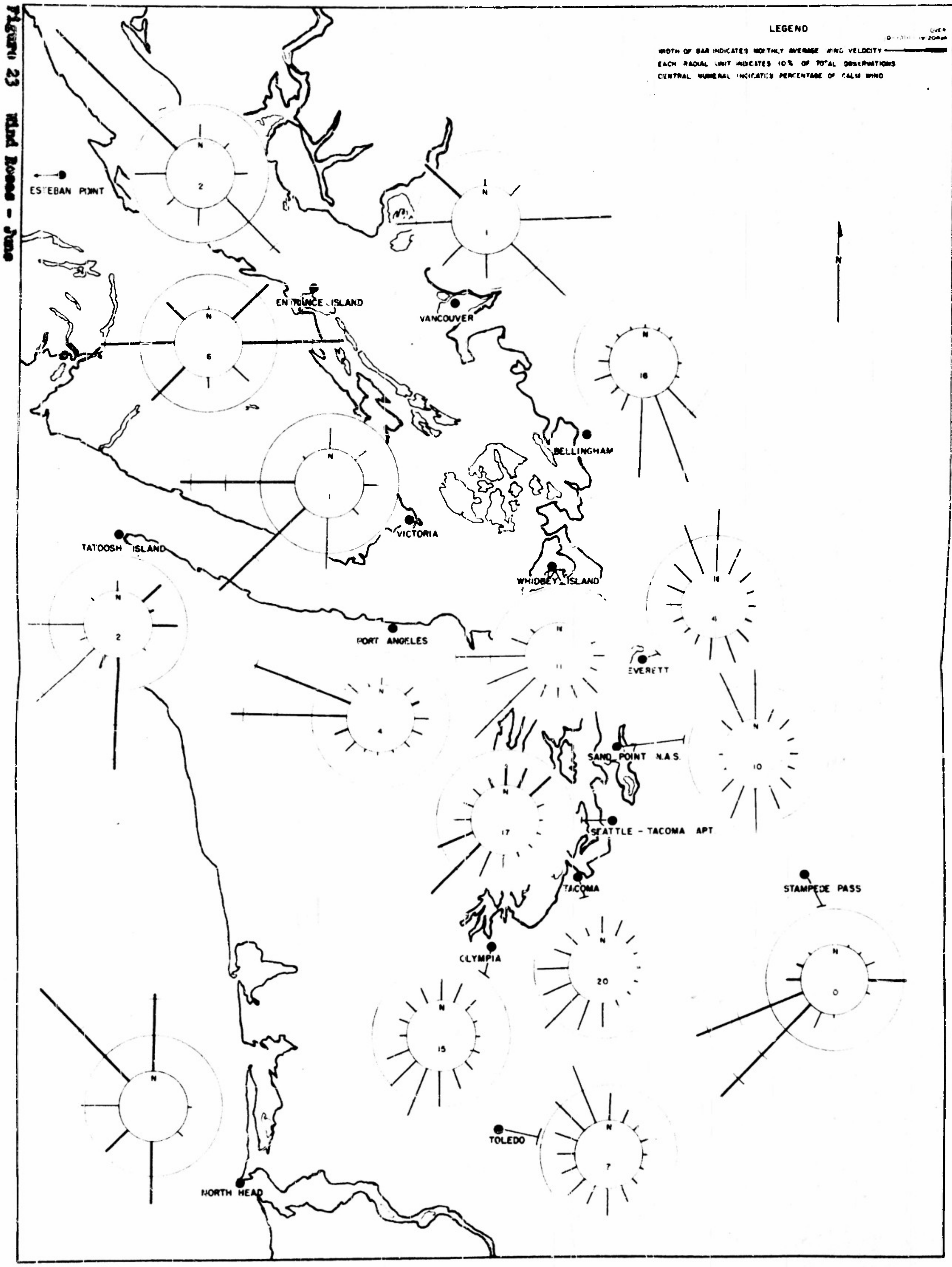

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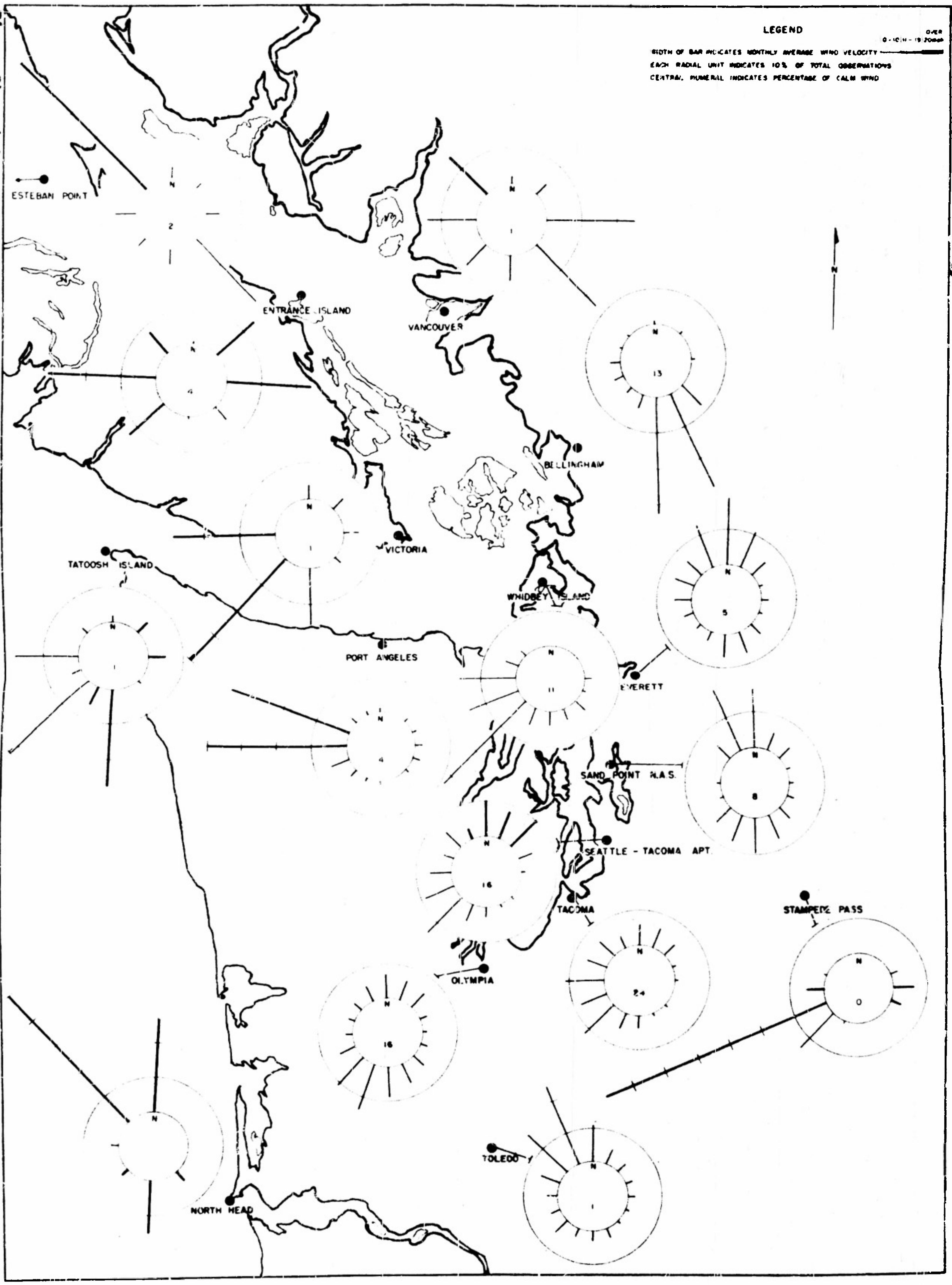

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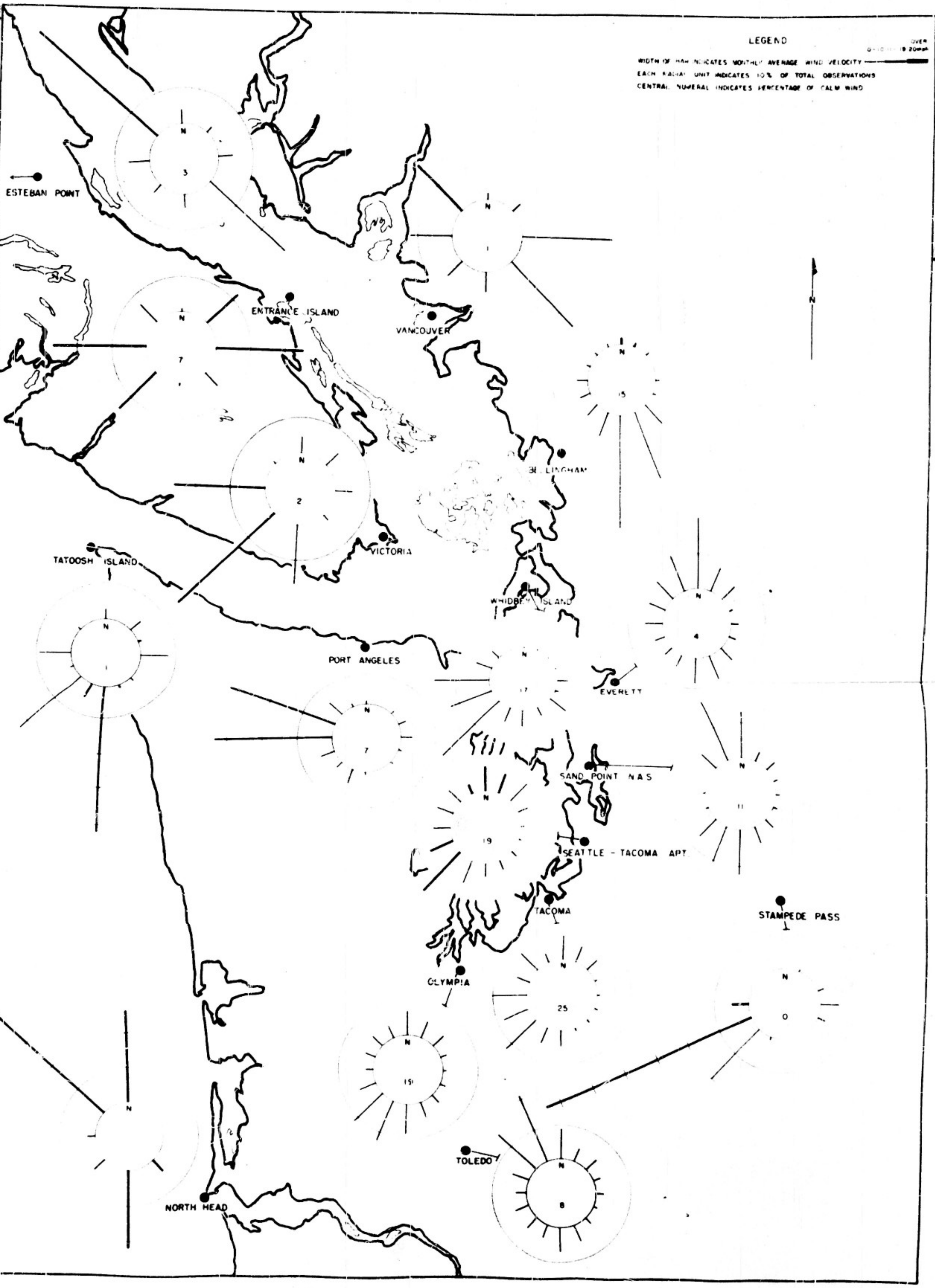

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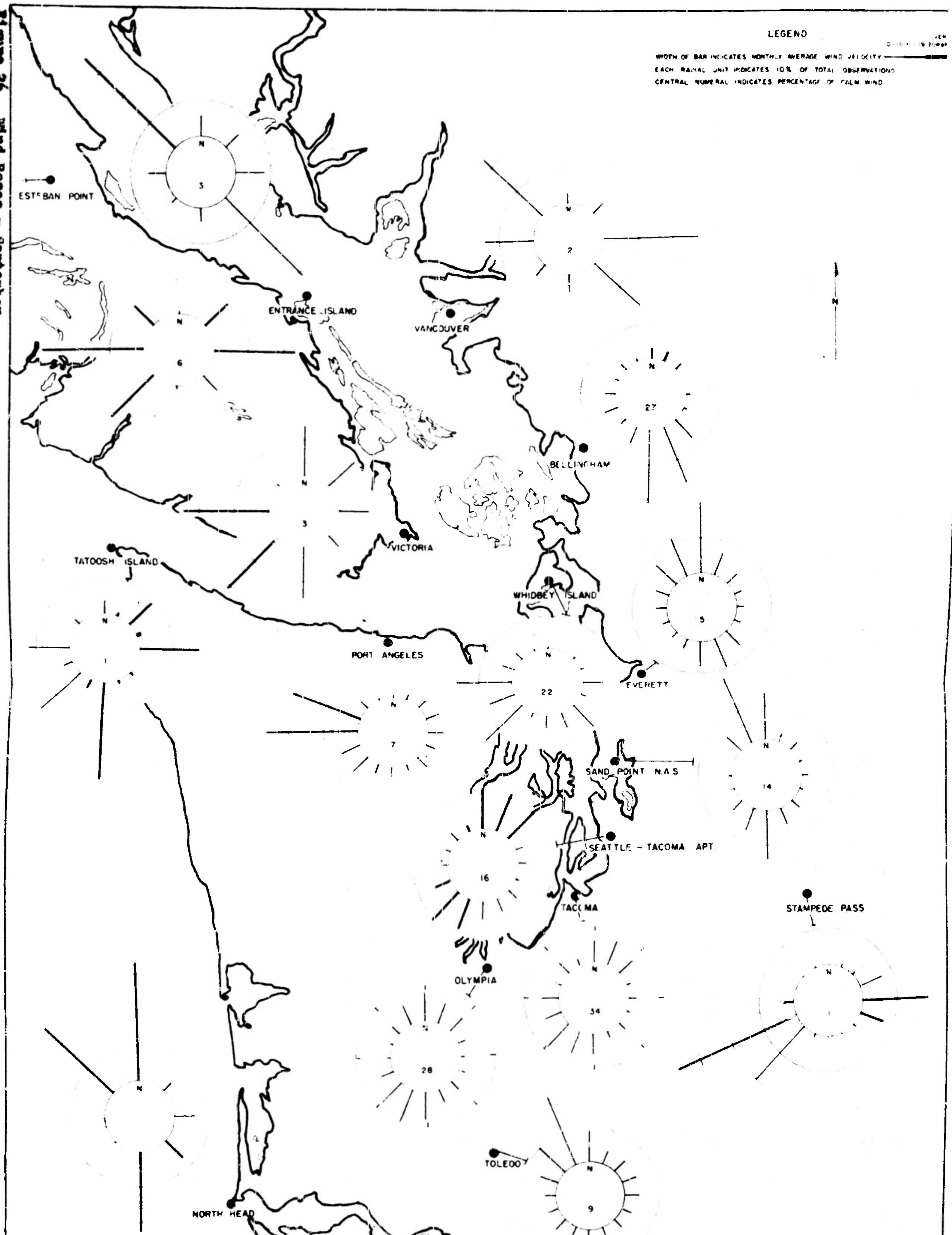

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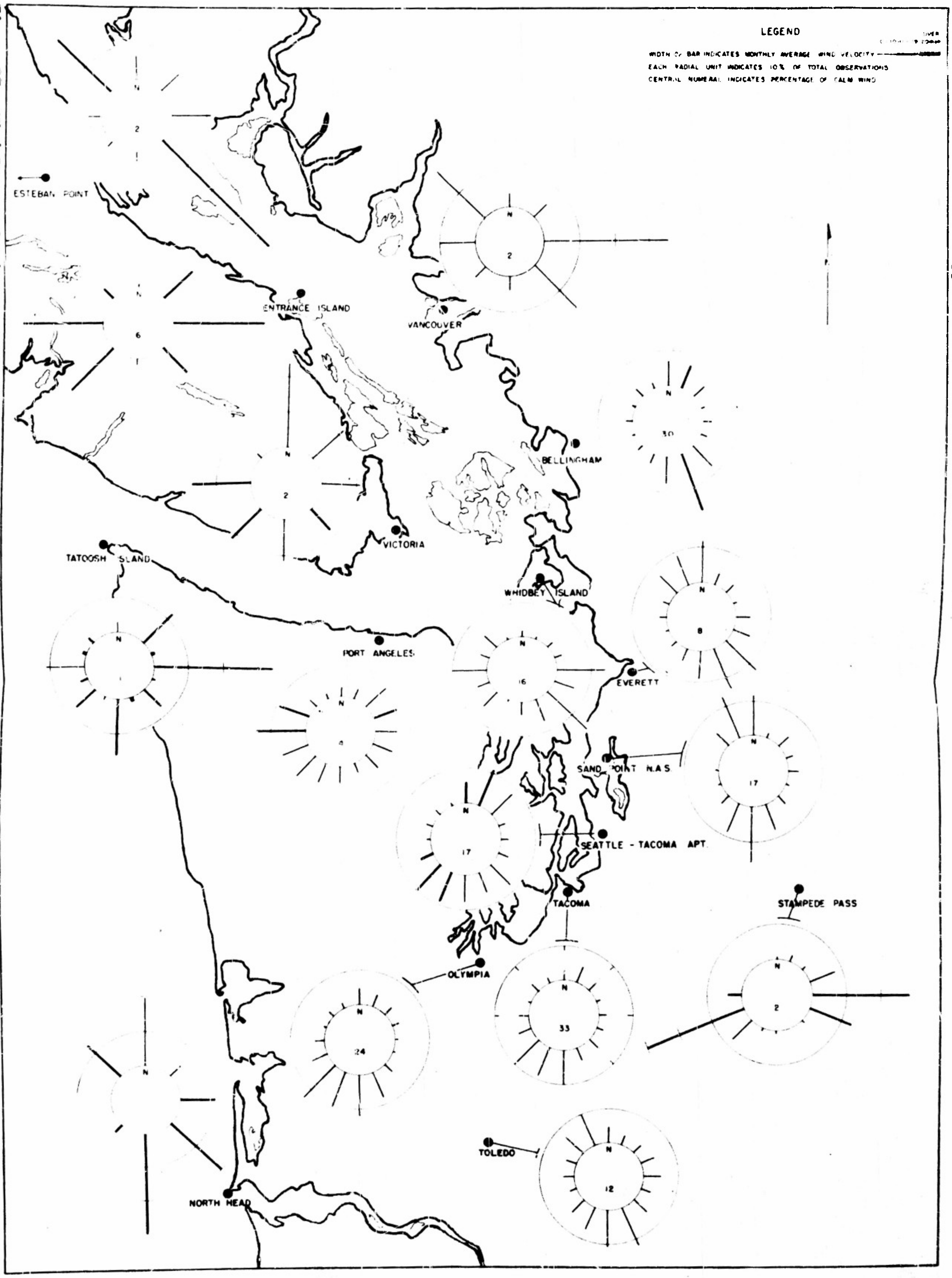

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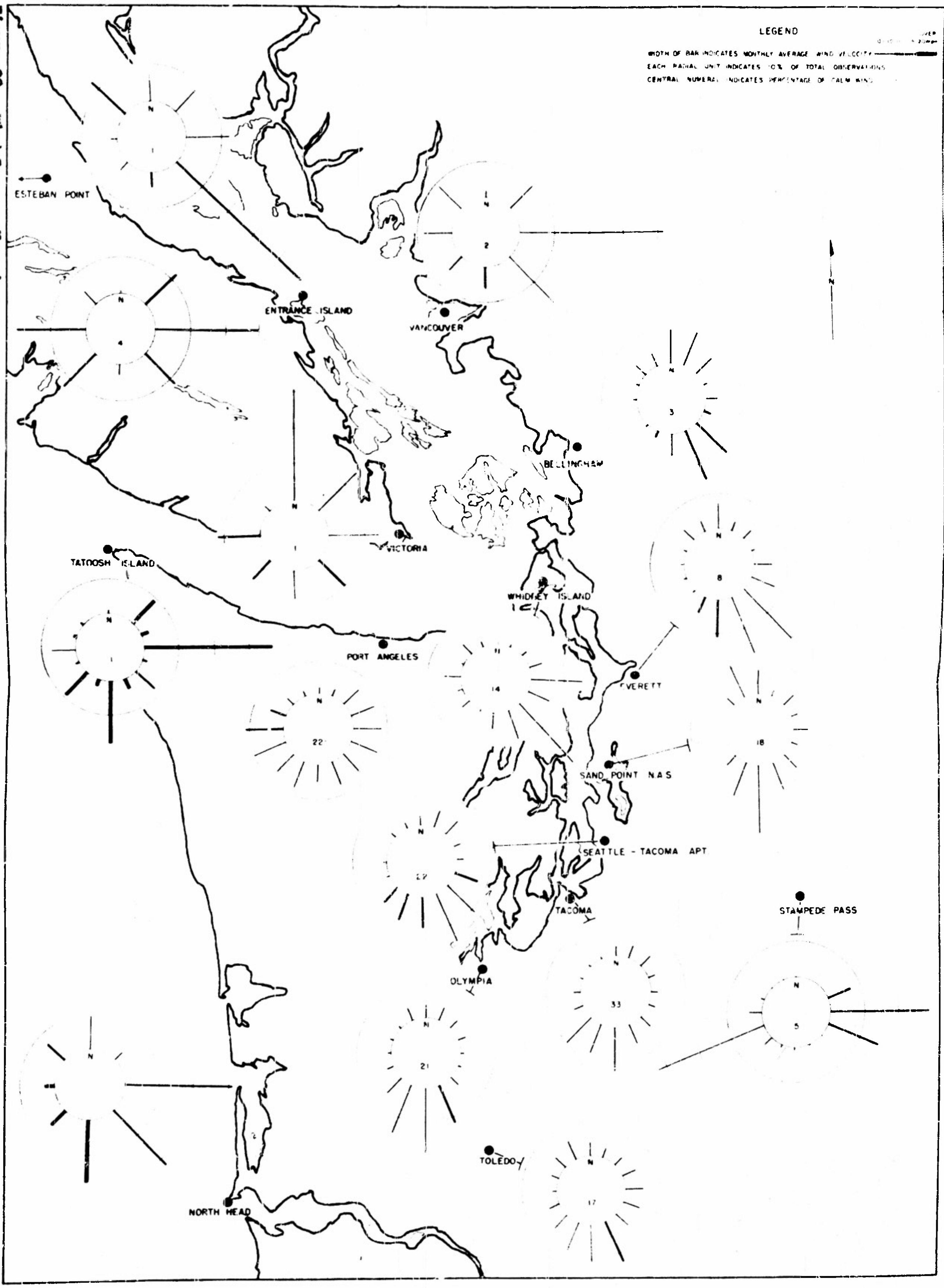

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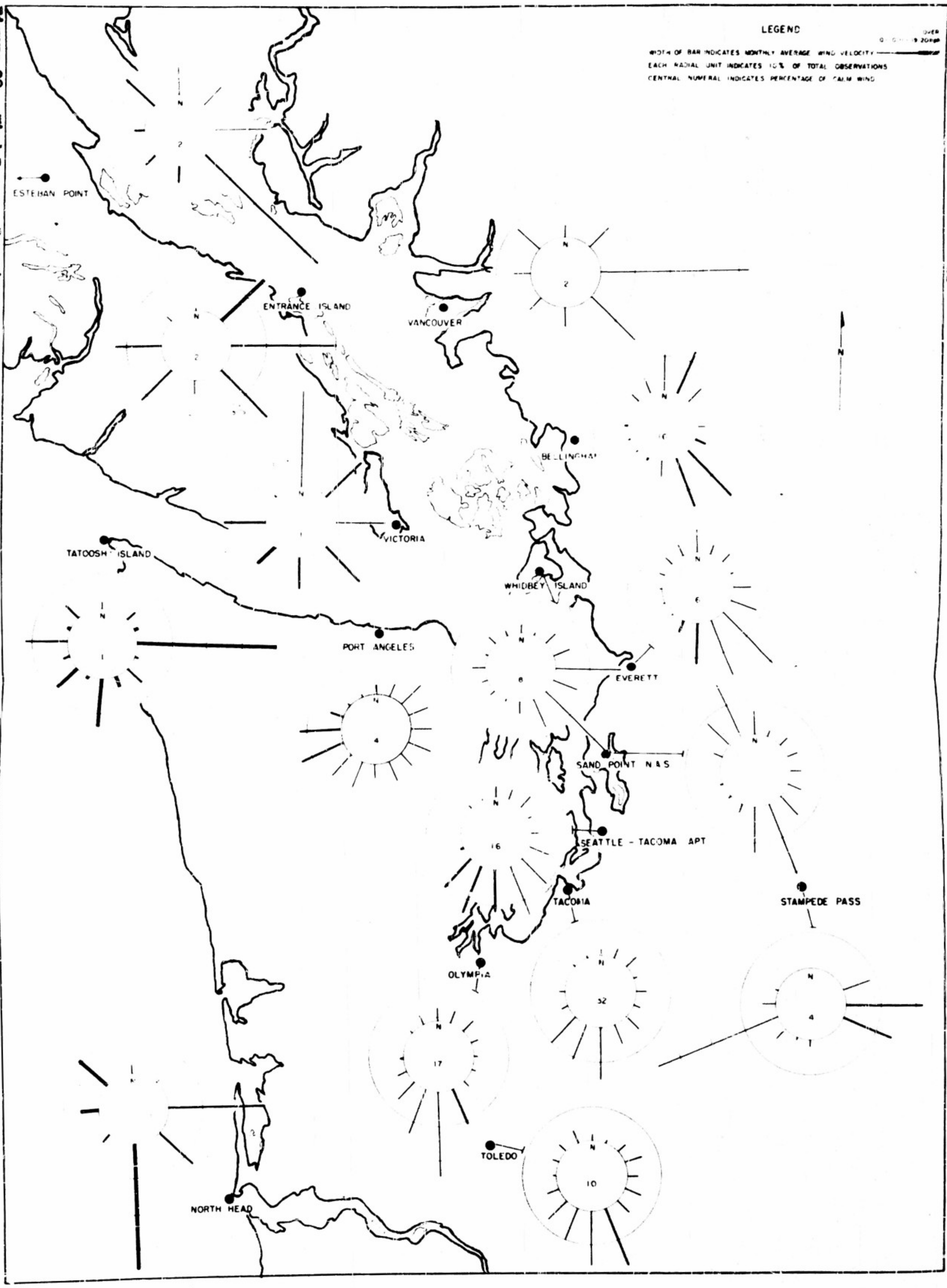

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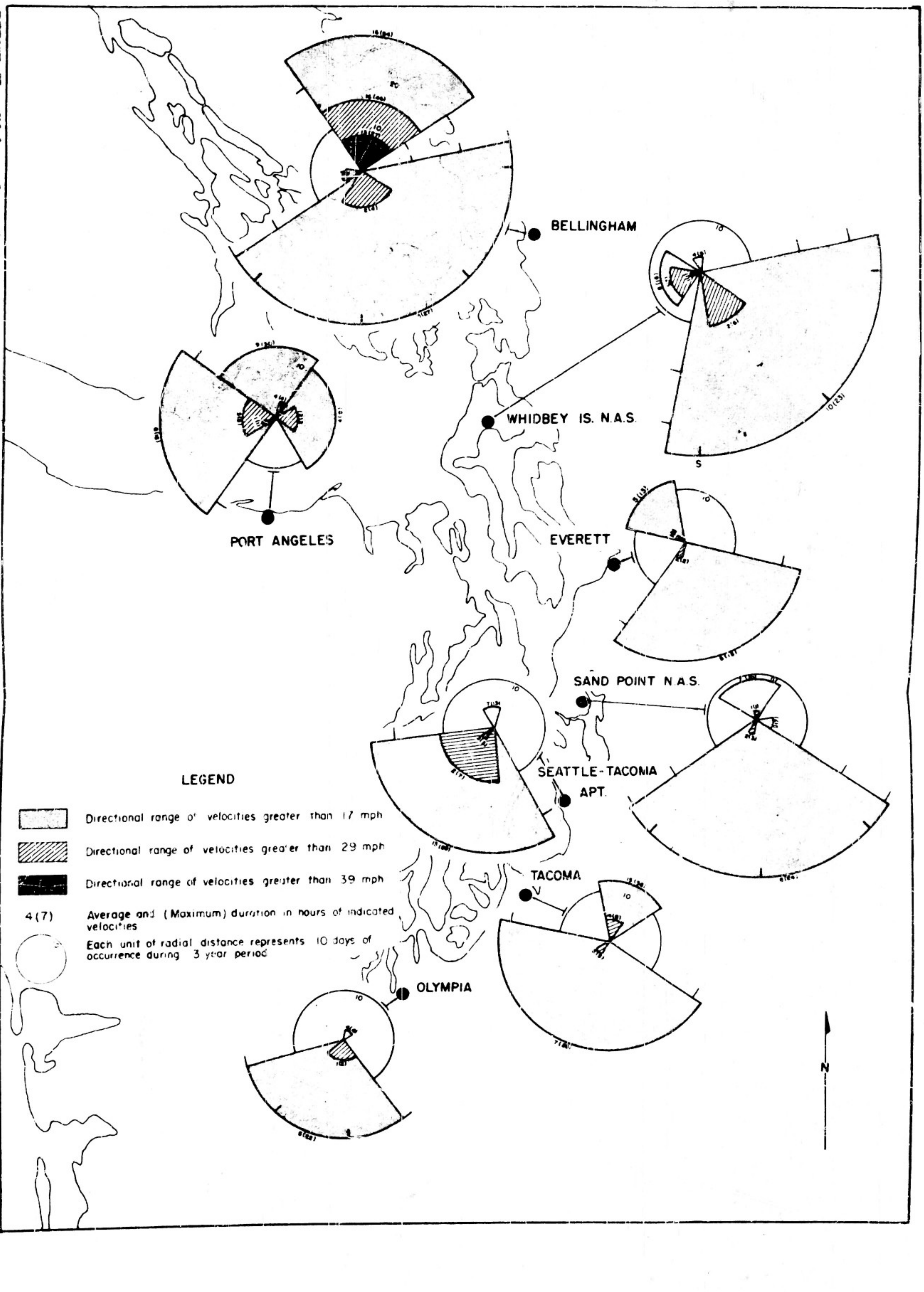
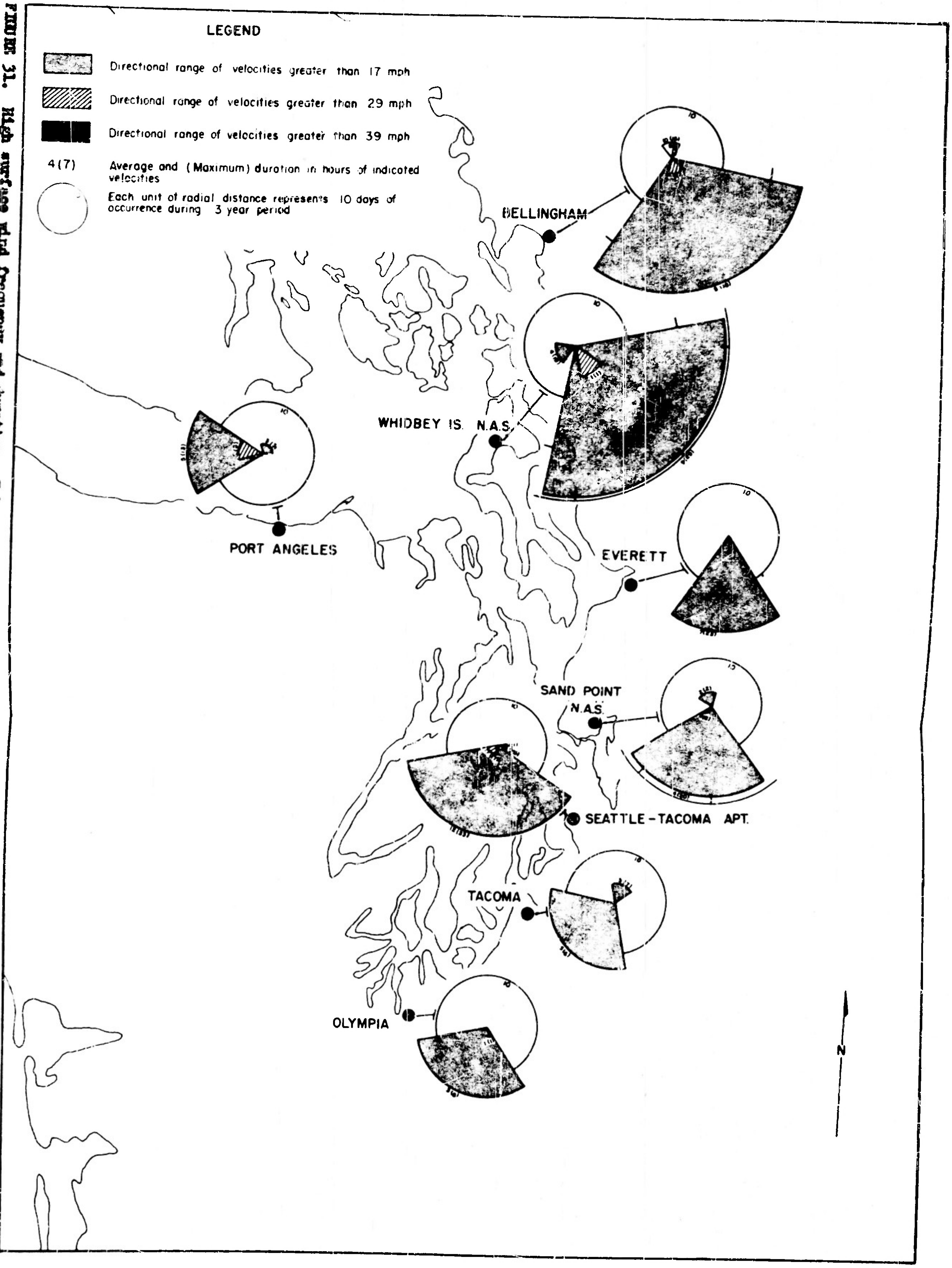


FIGURE 10. High surface wind frequency and duration - January.



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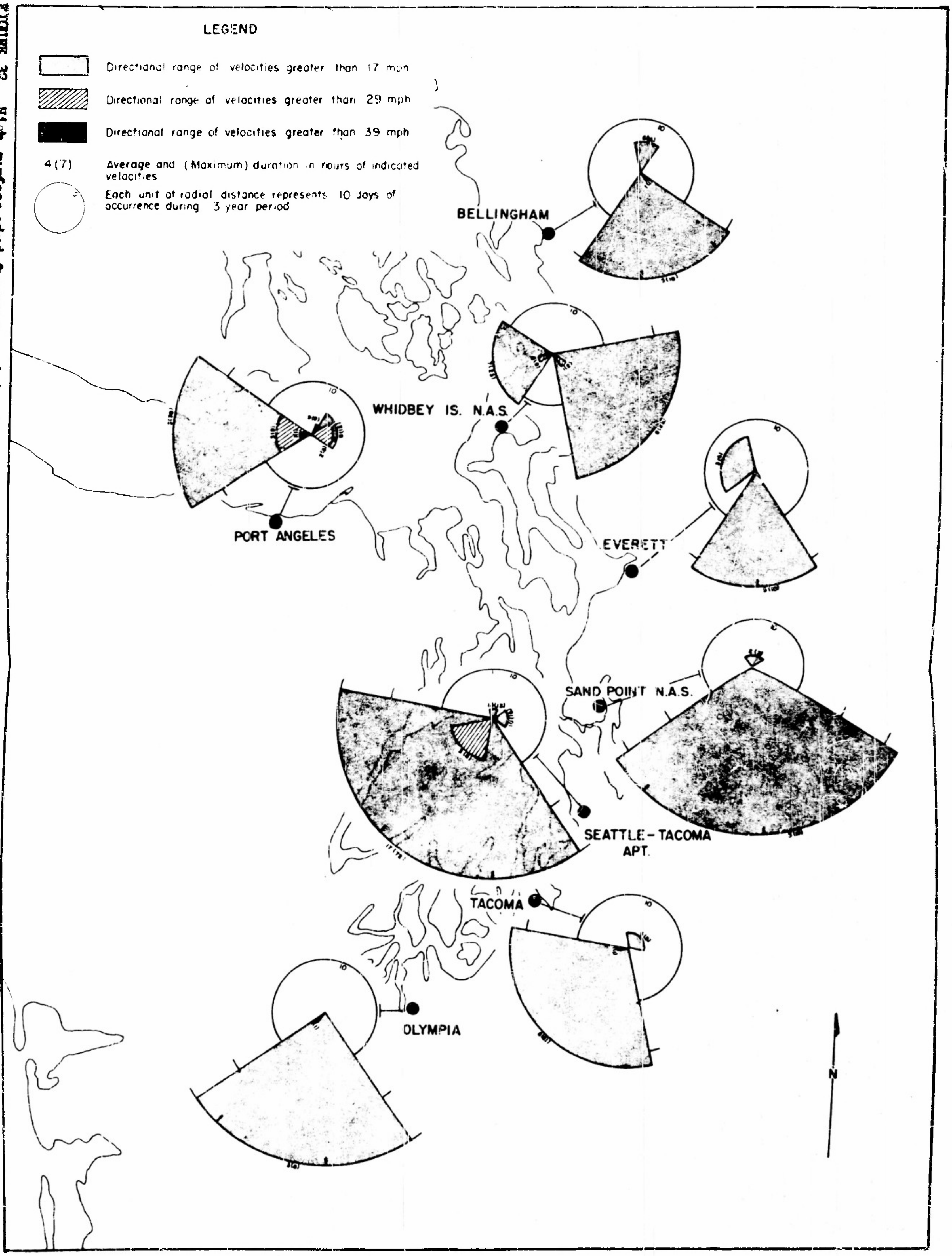

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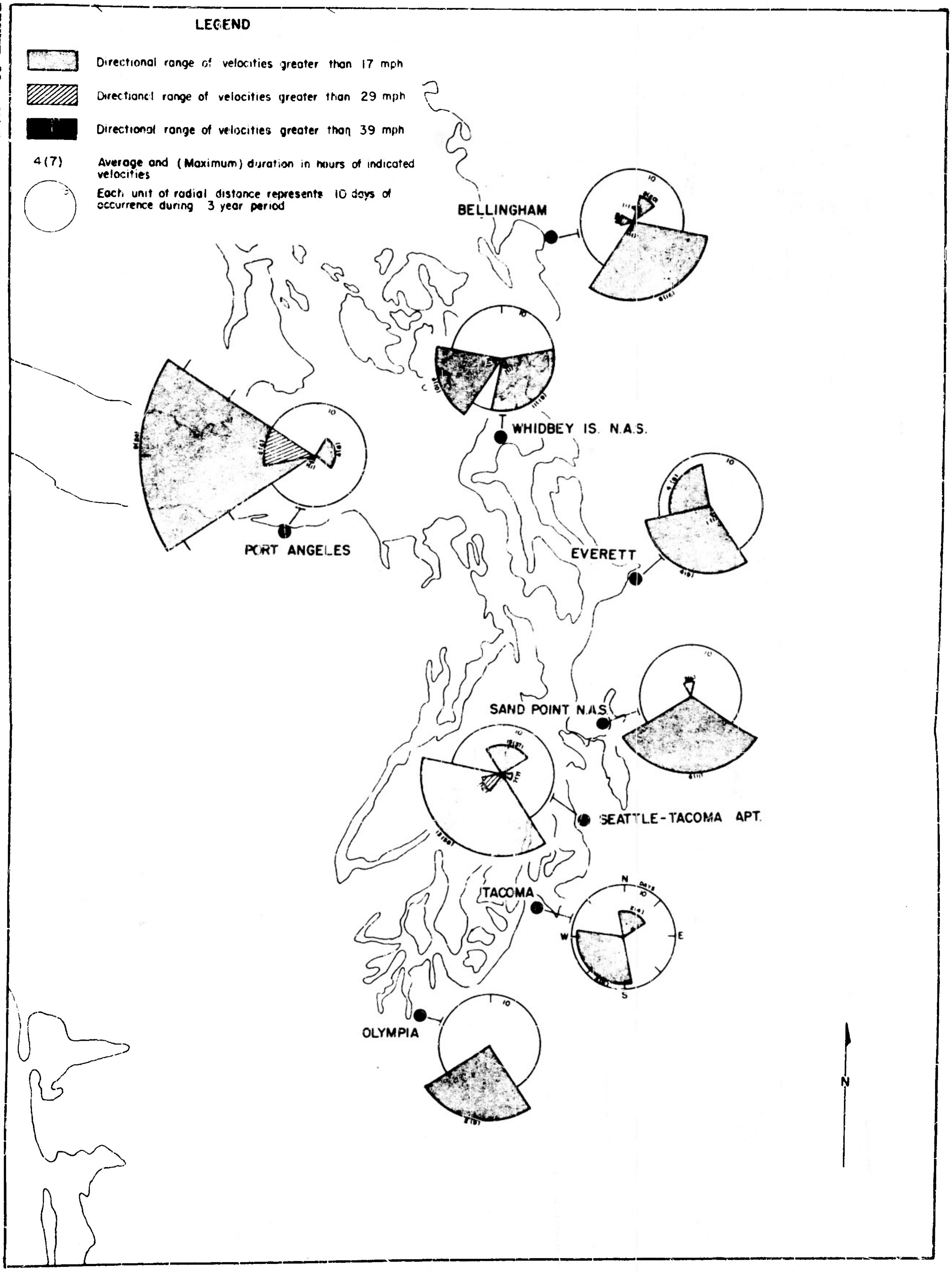

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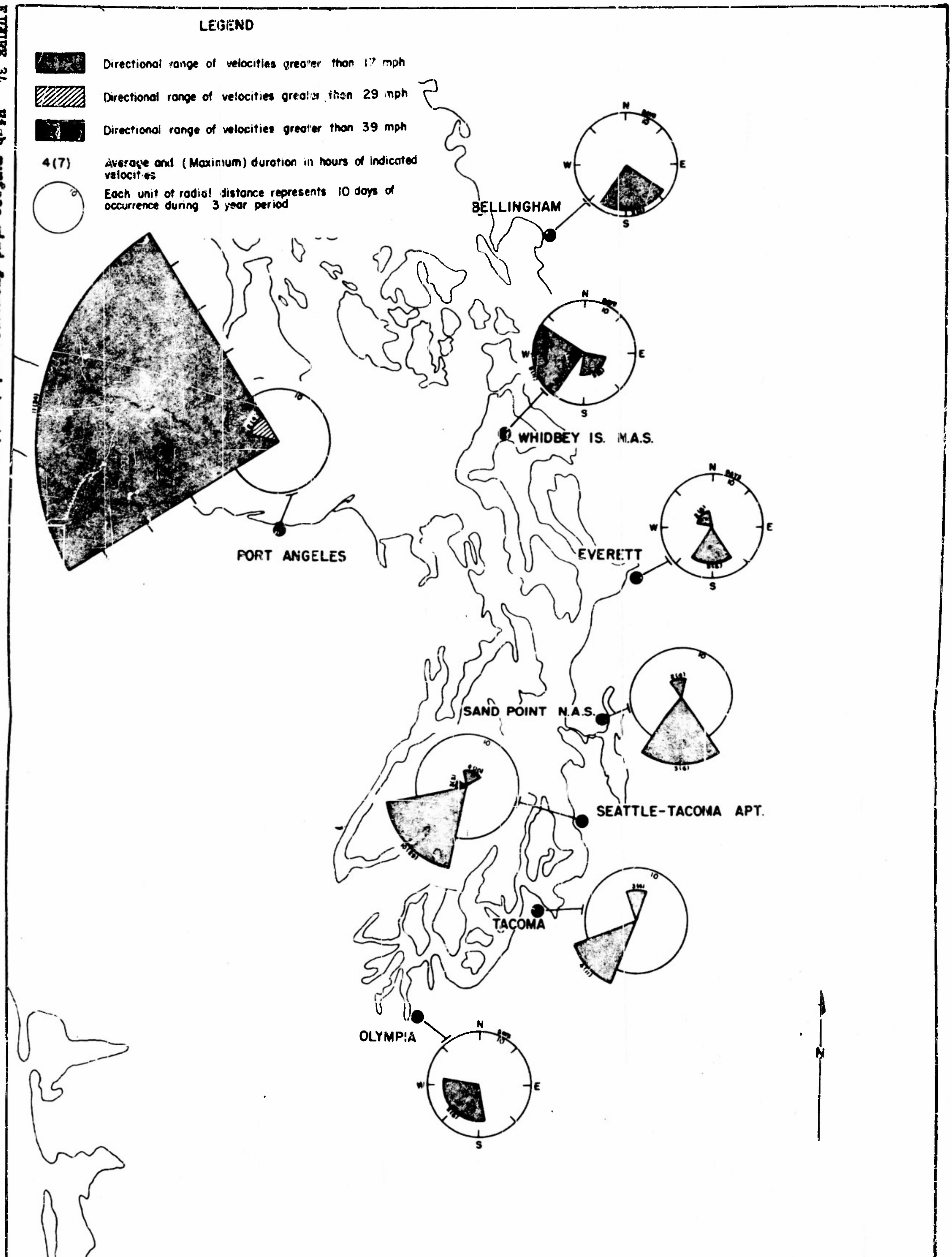

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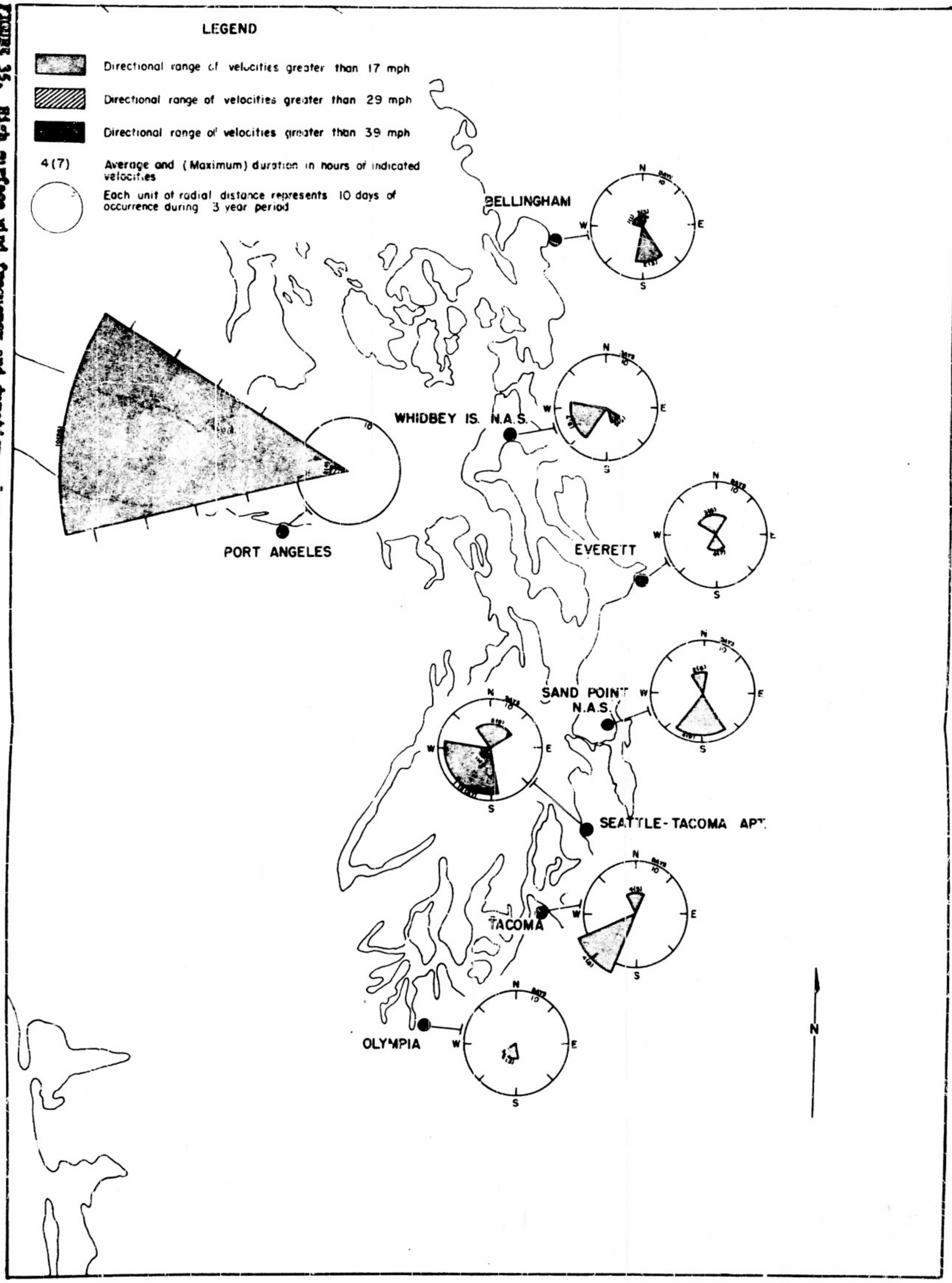

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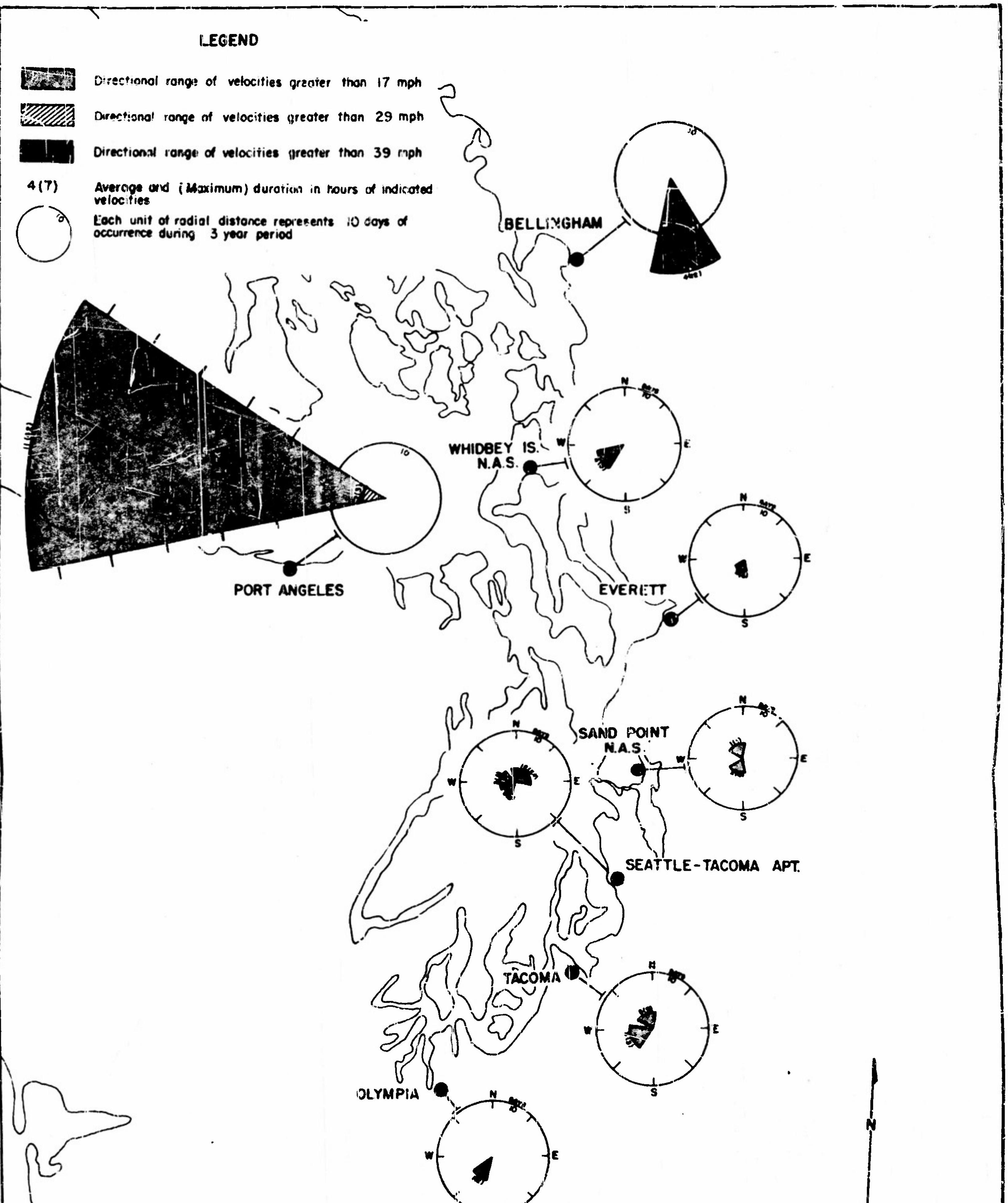

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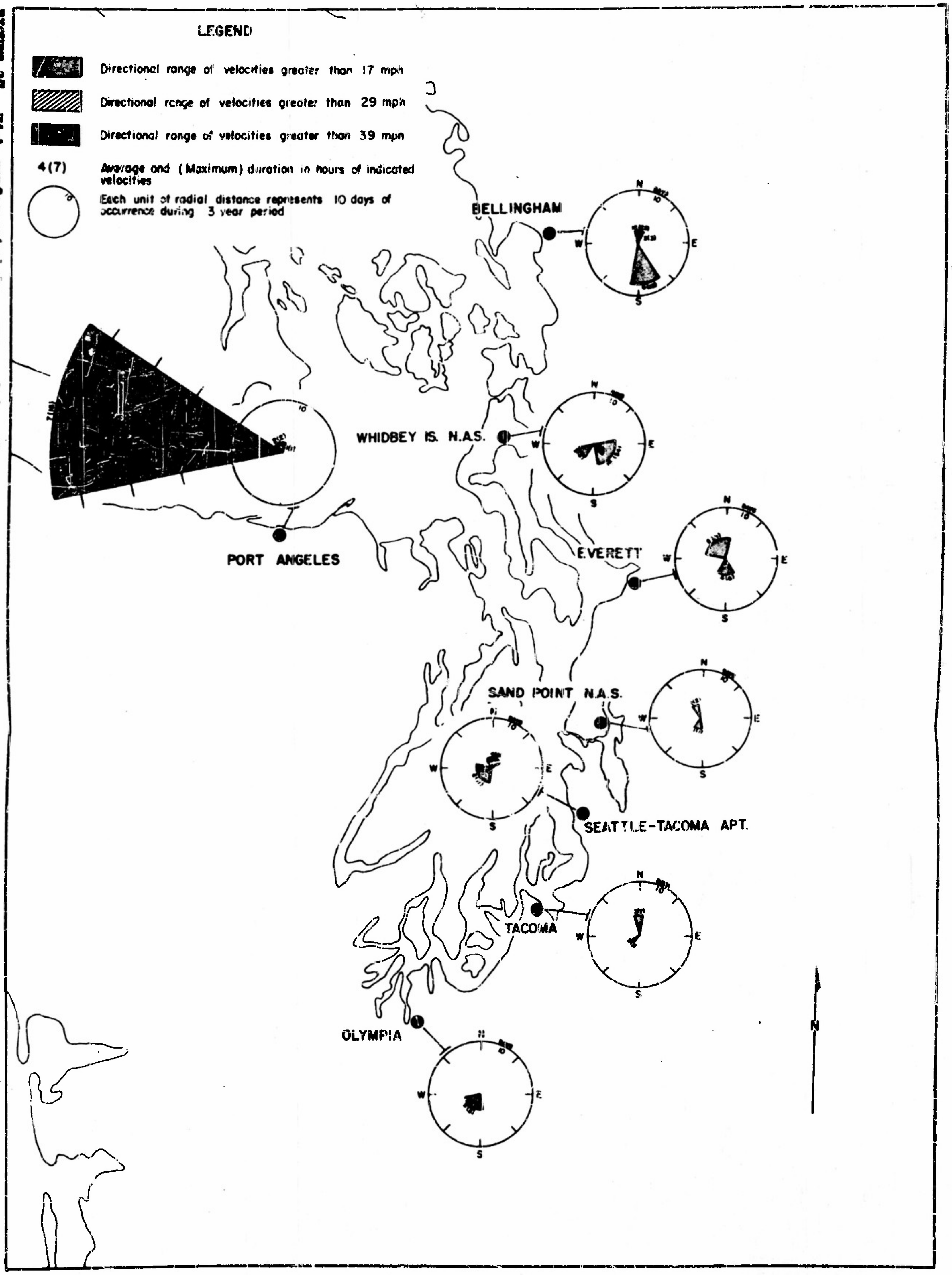

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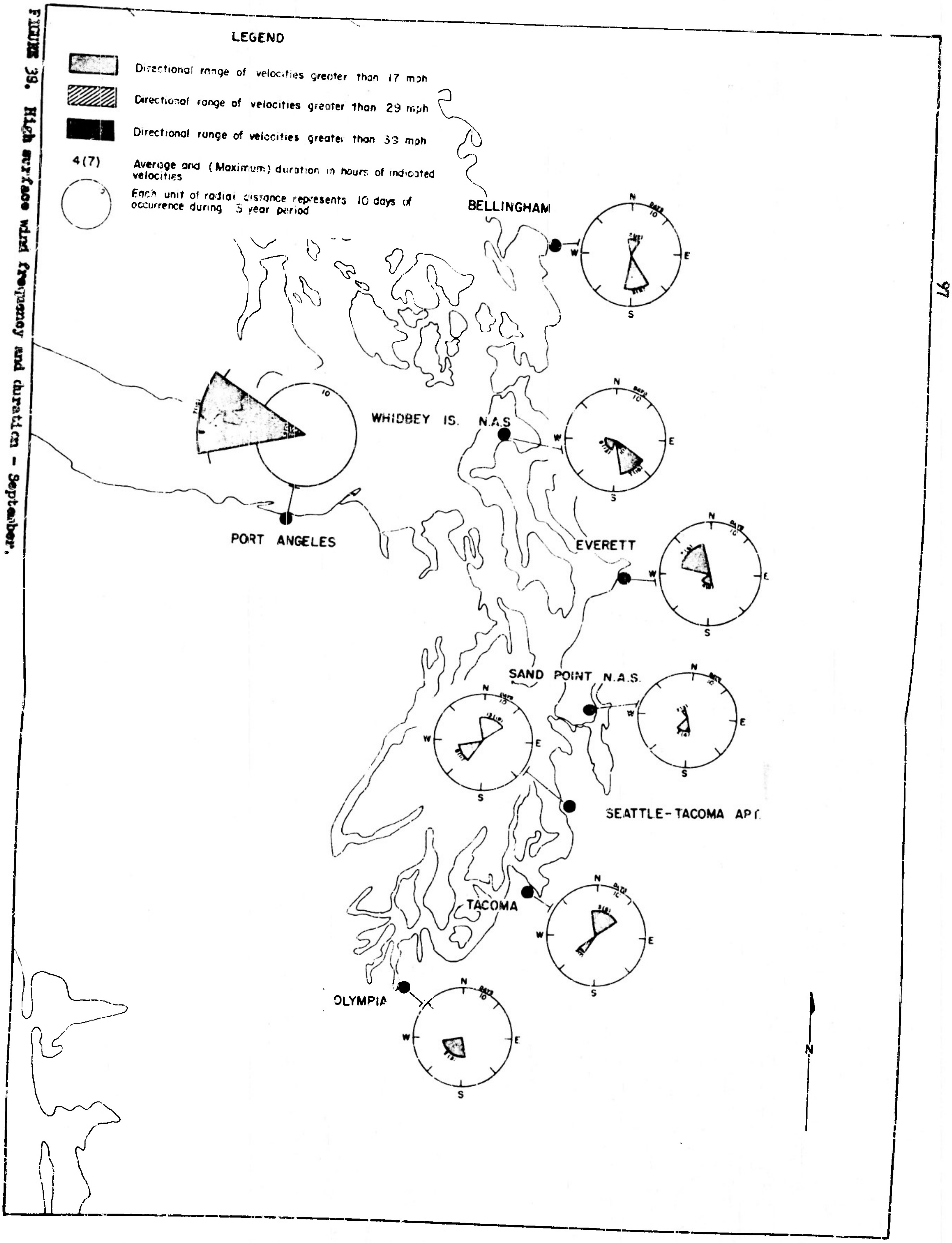

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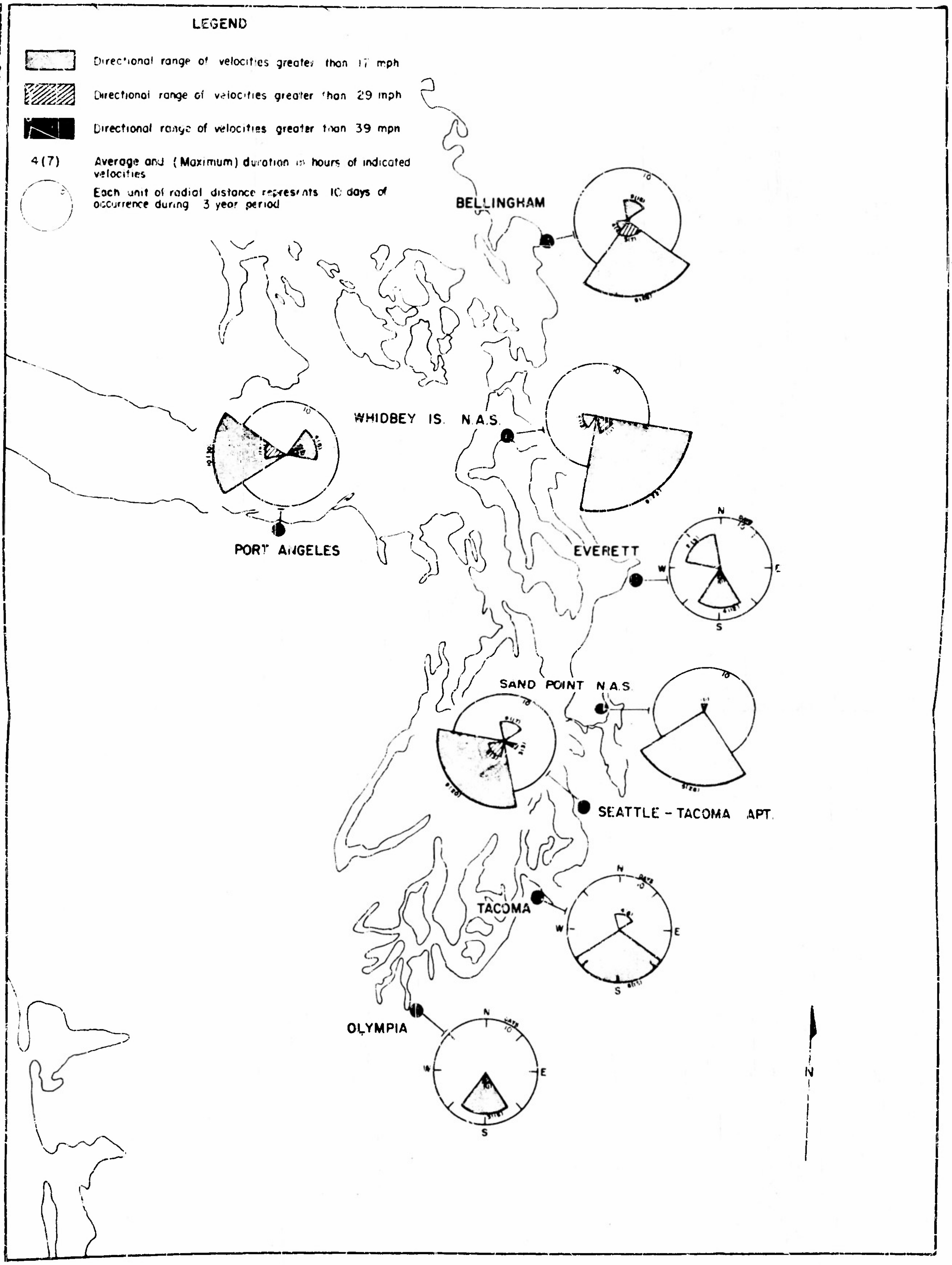

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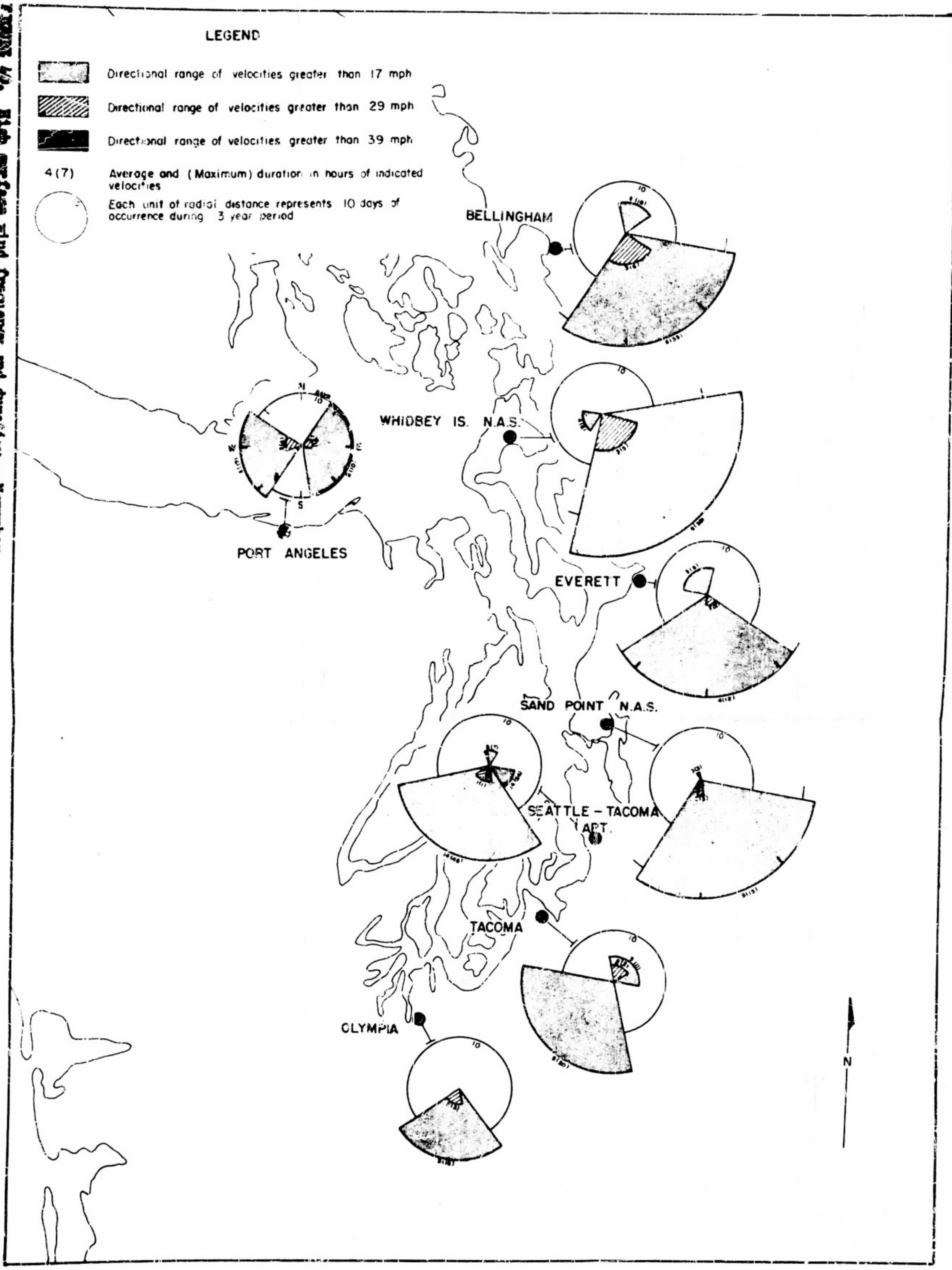

FIGURE 4/a. High surface wind frequency and duration - November.

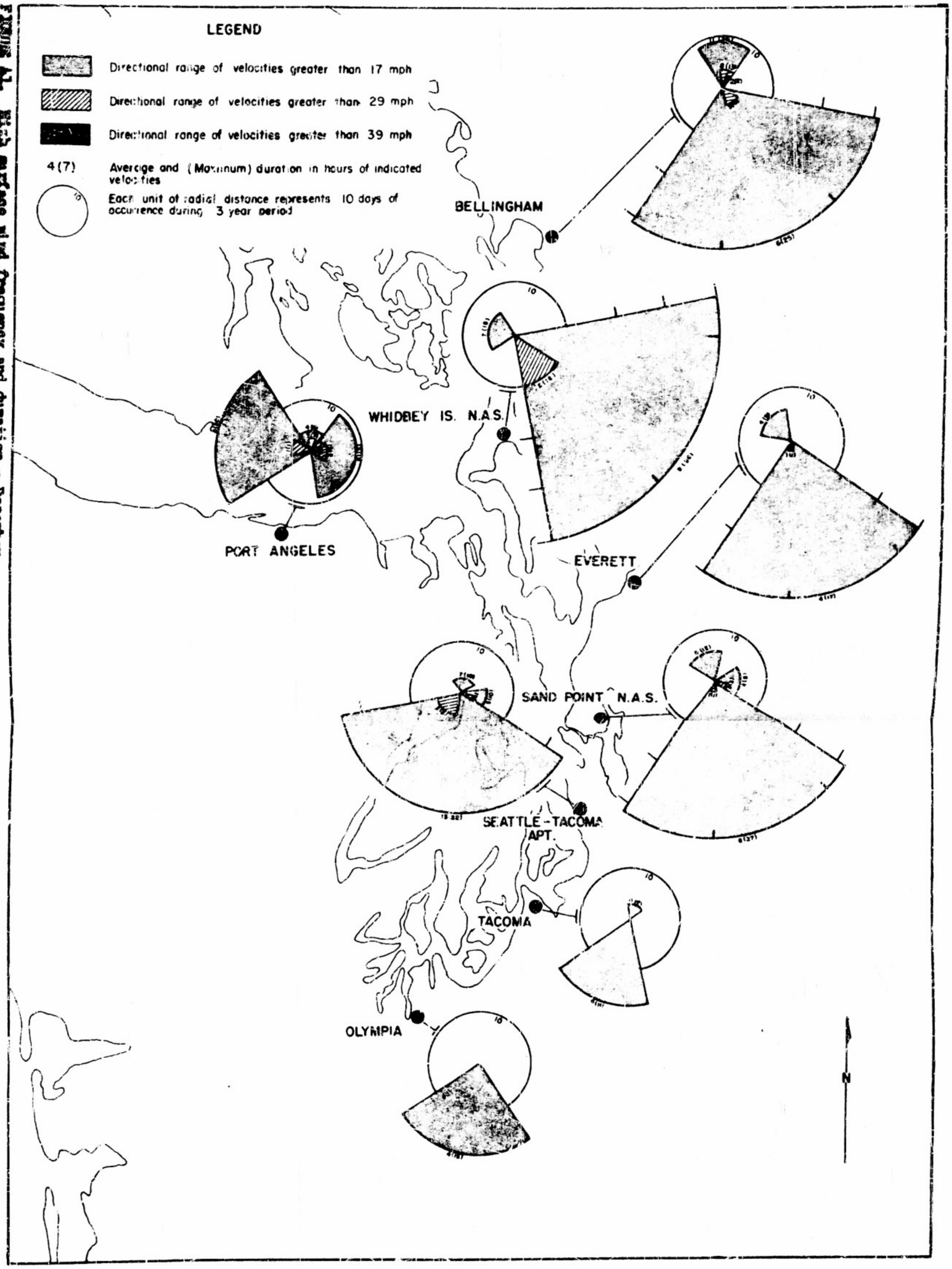

FIGURE A1. High surface wind frequency and duration - December.

LITERATURE CITED

Beamer, Carol C., "The Structure of Summer Wind Over San Juan Island, Washington", Yearbook of the Association of Pacific Coast Geographers III 31, 1937.

Department of Oceanography, University of Washington, "Oceanographic Survey on Submarine Portion of Snohomish-Kitsap 230 KV Line. Final Report. Part I." University of Washington, Seattle, Washington.

Gerlach, Arch C., "Precipitation of Western Washington," Ph.D. Dissertation 1943, Library, University of Washington, Seattle, Washington.

Munk, Walter H., "A Critical Wind Speed for Air-Sea Boundary Processes," Journal of Marine Research 6 (1947), p. 205-218.

Reed, Thomas L., "Gap Winds in the Strait of Juan de Fuca," Monthly Weather Review, 59: 373-376, 1931.

Stephens, Thomas E., "Temperatures in the State of Washington as Influenced by the Westward Spread of Polar Air Over the Rocky and Cascade Mountain Barriers", Master of Science Thesis, 1952, Library, University of Washington.

Sverdrup, Johnson and Fleming, "The Oceans", (New York: Prentice-Hall, 1949), p. 471-503.

United States Department of Agriculture, "Atlas of Climatic Charts of the Oceans," United States Weather Bureau, Washington, D.C., 1938.

United States Department of Commerce, "Tidal Current Charts, Puget Sound", Coast and Geodetic Survey, 1947.

United States Navy Hydrographic Office, "Techniques for Forecasting Wind Waves and Swell, "H.O. Publication No. 604, Washington, D.C., 1951.

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8 Hydrographer
U. S. Navy Hydrographic Office
Washington 25, D. C.
Attention: Division of Oceanography

1 Project Arowa
U. S. Naval Air Station
Building R-48
Norfolk, Virginia

2 Project Officer
Laboratory of Oceanography
Woods Hole, Massachusetts

5 Armed Services Technical Information Center
Documents Service Center
Knott Building
Dayton 2, Ohio

1 Assistant Secretary of Defense
(Research and Development)
Pentagon Building
Washington 25, D. C.
Attention: Committee on Geophysics and Geography

20 October 1954

1 Chief, Bureau of Aeronautics
Washington 25, D. C.
Attention: Code MA-S

1 Commandant (OAO)
U. S. Coast Guard
Department of the Treasury
Washington 25, D. C.

1 Commanding General
Research and Development Division
Department of the Air Force
Washington 25, D. C.

1 Commanding General
Research and Development Division
Department of the Army
Washington 25, D. C.

1 Commanding Officer
Air Force Cambridge Research Center
230 Albany Street
Cambridge 39, Massachusetts
Attention: CRHSL

1 Director, U. S. Coast & Geodetic Survey
Department of Commerce
Washington 25, D. C.

2 Director, U. S. Fish & Wildlife Service
Department of the Interior
Washington 25, D. C.
Attention: Dr. L. A. Walford

1 Dr. F. Møller, Norwegian Defense Research Institute
Akershus, Oslo, Norway

1 National Research Council
2101 Constitution Avenue
Washington 25, D. C.
Attention: Cimmittee on Undersea Warfare

1 Office of Technical Services
Department of Commerce
Washington 25, D. C.

1 Pacific Oceanographic Group
c/o Pacific Biological Station
Nanaimo, British Columbia, Canada

1 South Pacific Fishery Investigations
U. S. Fish & Wildlife Service
P. O. Box 271
La Jolla, California

1 U. S. Army Beach Erosion Board
5201 Little Falls Road N.W.
Washington 16, D. C.

1 U. S. Fish & Wildlife Service
Fort Crockett
Galveston, Texas

1 U. S. Fish & Wildlife Service
P. O. Box 3830
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1 U. S. Fish & Wildlife Service
Woods Hole, Massachusetts

1 Allen Hancock Foundation
University of Southern California
Los Angeles 7, California

1 Bingham Oceanographic Foundation
Yale University
New Haven, Connecticut

1 Department of Conservation
Cornell University
Ithaca, New York
Attention: Dr. J. C. Ayers

1 Department of Engineering
University of California
Berkeley, California

1 Department of Meteorology & Oceanography
College of Engineering
New York University
University Heights, New York 53, N.Y.
Attention: Dr. W. J. Pierson

1 Department of Zoology
Rutgers University
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Attention: Dr. H. K. Haskins

1 Director, Bermuda Biological Station for Research
St. George's, Bermuda

1 Director, Chesapeake Bay Institute
Box 426A, R.F.D. #2
Annapolis, Maryland

1 Director, Hawaii Marine Laboratory
University of Hawaii
Honolulu, T. H.

1 Director, Lamont Geological
Observatory
Torrey Cliff
Palisades, New York

1 Director, Marine Laboratory
University of Miami
Coral Gebles, Florida

1 Director, Narragansett Marine
Laboratory
University of Rhode Island
Kingston, Rhode Island

1 Director, National Institute of
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Wormley, Near Godalming
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2 Director, Scripps Institution of
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1 Head, Department of Oceanography
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1 Institute of Oceanography
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1 The Oceanographic Institute
Florida State University
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